



Test and Approval Center for Fuel Cell and Hydrogen Technologies: Phase I. Initiation Final report

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Test and Approval Center for Fuel Cell and Hydrogen Technologies: Phase I. Initiation

Test- og Godkendelsescenter for Brændselscelle- og Brintteknologier: Fase 1. Opstart

Final Report

DTU Energy Conversion



DGC

Rådgivning, udvikling og måling inden for energi og miljø

TOPSOE FUEL CELL
RETHINKING ENERGY



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Department of Energy Conversion and Storage
DTU, Risø Campus
September 2012

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Introduction

Fuel cells and hydrogen technologies hold the potential for decreasing emissions of greenhouse gases and air pollutants, for facilitating the increased use of renewable energy sources with high efficiencies and thereby contributing to the establishment of a sustainable energy system and the mitigation of the human-caused global warming. Fuel cells (in particular solid oxide fuel cells) produce electricity and heat at higher efficiencies than conventional power plants. They emit less pollutants - for example no toxic NO_x at all - than conventional plants do. Fuel cells can operate on fossil fuels (natural gas) and on alternative fuels as well. They can therefore bridge the gap between availability and efficient use of fossil fuels on the short term and establishment of an energy market based on renewables on the long term. Hydrogen is a zero carbon energy carrier that— just like electricity - can be converted to power and heat. The increased use of hydrogen will decrease oil dependency, which is foreseen to have profound economic as well as political impacts.

Fuel cell and hydrogen technologies play an important role in future sustainable energy system scenarios, often in combination with other technologies where Denmark already holds strong positions today. This includes for example (1) using biomass for production of electricity, (2) storing of energy by using excess electricity from wind turbines to produce fuel by electrolysis and (3) using fuel cells for load balancing of the fluctuating wind energy.

As the fuel cell and hydrogen technologies come closer to commercialization, development of testing methodology, qualified testing and demonstration become increasingly important.

Danish industrial players have expressed a strong need for support in the process to push fuel cell and hydrogen technologies from the research and development stage into the commercial domain. A Center to support industry with test, development, analysis, approval, certification, consultation, and training in the areas of fuel cell and hydrogen technologies was needed.

Denmark has demonstrated leading international positions in the fuel cell and hydrogen technologies. The expectations from the center were to secure a continuing strong position for Denmark in these fast developing areas in the near and far future. Furthermore, the center was considered necessary to secure that the substantial investments already spent on these technologies also lead to commercial success.

The project 'Test and Approval Center for Fuel Cell and Hydrogen Technologies: Phase I. Initiation' was aiming at starting with the Establishment of such a center. The following report documents the achievements within the project. This is done by compiling short reports for each milestone that illustrate the related activities. The official reports are included in this final report. Furthermore, an account for the dissemination of the project results and the Center as such is given and, finally, the final EUDP scheme for the project.

Resumé

Projektets formål var at starte med et Test- og Godkendelsescenter for Brændselscelle- og Brintteknologier (arbejdspakke 1) og at påbegynde de første aktiviteter på udvikling af accelererede levetidstests af brændselscellesystemer, forberedelse for standardisering af disse

metoder og rådgivning i forbindelse med certificering af brændselscellesystemer (arbejdspakke 2).

Hovedresultater er:

Arbejdspakke 1:

- Et stort nationalt og internationalt netværk blev etableret, som omfatter vigtige industrielle spillere, forskningsinstitutioner og andre testcentre
- Det lykkedes at gøre testcenteret kendt i store dele af den internationale brændselscelle- og brintverden
- Et antal nye projekter med afgørende roller for testcenteret er blevet ansøgt og bevilliget, både nationalt og internationalt, som sikrer den videre etablering og udvikling af testcenteret

Arbejdspakke 2:

- Nyt udstyr til brændselscelletest blev installeret og taget i brug på DTU (Risø campus)
- En omfattende undersøgelse af internationale aktiviteter omkring accelereret levetidstest blev gennemført
- En testprotokol for højtemperaturbrændselscelletest med udgangspunkt i anvendelse på mikrokraftvarmeområdet blev udviklet og anvendt på enkeltcelle- og 50-cellestakke
- En vejledning for myndighedshåndtering blev formuleret

Summary

The aim of the present project was to initialize a Test and Approval Center for Fuel Cell and Hydrogen Technologies at the sites of the project partners Risø DTU (Fuel Cells and Solid State Chemistry Division), and DGC (work package 1). The project furthermore included start-up of first activities with focus on the development of accelerated life-time tests of fuel cell systems, preparations for standardization of these methods, and advising in relation to certification and approval of fuel cell systems (work package 2).

The main achievements of the project were:

Work package1:

- A large national and international network was established comprising of important commercial players, research institutions, and other test centers
- The test center is known in large part of the international Fuel Cell and Hydrogen community due to substantial efforts in 'marketing'
- New national and international projects have been successfully applied for, with significant roles of the test center, which secure the further establishment and development of the center

Work package2:

- Testing equipment was installed and commissioned at DTU (Risø Campus)
- A comprehensive survey among international players regarding activities on accelerated SOFC testing was carried out
- A test procedure for 'compressed' testing of SOFC in relation to μ CHP application was developed and used for one-cell stack and 50-cell-stack testing

- Guidelines for Danish authority handling were formulated

Outlook

The vision for the Center is to become the Preferred European Test Center in the areas of fuel cells and hydrogen in order to facilitate commercialization of fuel cell and hydrogen technologies (climate, environment goals) utilizing internationally recognized strengths that Denmark has and is increasing within these fields thereby contributing to securing and further developing this position (Danish work places, technology export).

With this project, the basis was laid to fulfil this mission. Already within the project period, there has been focus on continuing with the establishment of the Center by initiating and participating in national and international consortia and by application for projects. The first commercial activities in regard to testing have started.

Also the future activities of the test center will be based on demonstrated Danish competences and will in turn promote further research, development and education, both at academia and industry. The test center will facilitate the attraction of international players and help to increase the international reputation Denmark has in these technologies.

The center will further develop through active participation and coordination of national and international projects, through keeping and extending its national and international network with industry and academia and through a close evaluation of the actual market situation and corresponding adjustment.

Milestones

Complete list of milestones

Project period	2010				2011				2012	
Activity/Milestone	I	II	III	IV	I	II	III	IV	I	II
1.1 Market introduction and marketing of the Center										
I) Formulation of marketing plan		◆								
II) Homepage and flyer			◆							
III) Presentation Danish industry				◆						
IV) Press mention										◆
V) Presentation of center at an international conference								◆		
1.2 Establishment of an Advisory board & start of interaction with Center; networking with industrial players and relevant international institutions										
I) Decision about participants		◆								
II) Kick-off meeting		◆								
1.3a Preparation and start of phase II, (def. of & application for projects)										
I) Preliminary financing plan for center			◆							
II) Application of Green Lab DK				◆						
III) Application of appropriate projects							◆			
IV) Financing of phase II secured by appropriate applications										◆
1.3b Preparation of phase III (definition and prioritizing of activities)										
1.4 Finalizing of road maps for the Center development										
I) Proposal roadmap			◆							
II) Revised roadmap								◆		◆
2.1 Installation, development and performance of accelerated life-time tests of fuel cell systems										
I) Project outline defined				◆						
II) Accelerated test procedure proposed							◆			
III) Accelerated test procedure defined										◆
2.2 Standardisation issues of accelerated fuel cell testing										
I) Report of standardisation pre-survey				◆						
II) Meeting of interest group for standard development							◆			
III) Formulation discussion basis							◆			
IV) Formulation of 1 st draft version of standard										◆
2.3 Consultancy in relation to certification & approval										
I) Instruction guidelines for handling with authorities in the fuel cells & hydrogen area outside the process industry in Denmark										◆

Short milestone reports

Milestone 1.1 I

Activity/Milestone
1.1 Market introduction and marketing of the Center
I) Formulation of marketing plan

A marketing plan was formulated as integral part of the GreenLabs application. The introductory part of this plan is shown below, for the complete plan see the GreenLabs application.

5.7 Marketing plan

The present marketing plan covers the activities which will be carried out to market the test center to the customers (target groups). The plan reflects the fact that the industry has emerging growing need for testing and other services. Until the full test capacity has been reached in 2014, the test center will focus its services based on the close dialogue with the known Danish companies. The implication for the marketing plan is that the test center from a starting point will focus on “corporate” marketing and PR activities and postpone most product marketing to a later stage, when the test capacity is available. The most important challenge for the test center will be to establish itself as a well known, acknowledged center of excellence by creating awareness activities in a number of ways, and breaking down the geographical barriers. The test center will build its reputation over time through satisfied customers and awareness in the market.

In the following, the market for the four **Risø FCH Test Center** business areas – testing, consultancy, training, and certification – will be evaluated as one market since the individual market segments for these services currently are small. As the market segments develop, the dynamics of each segment will be evaluated and be part of the yearly strategy process, in order to position the **Risø FCH Test Center** services and products correctly in the competitive landscape.

Milestone 1.1 II

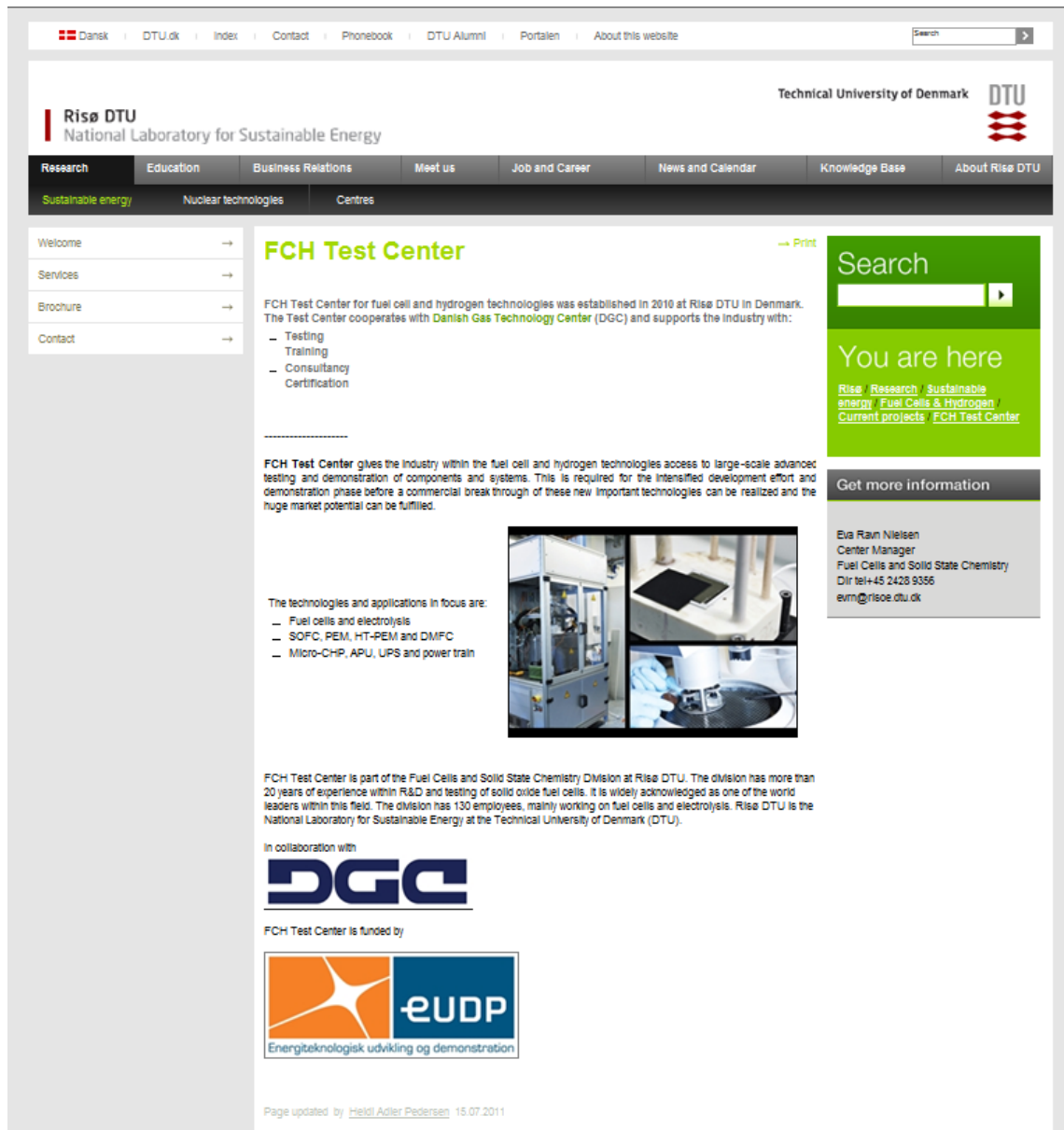
Activity/Milestone

1.1 Market introduction and marketing of the Center

II) Homepage and flyer

A homepage (www.fch.dk) and a flyer were created informing about the center, participants, aims, services, financing etc. the flyer can be down loaded from the homepage as well.

Welcome page:



The screenshot shows the homepage of the FCH Test Center. The header includes navigation links for Dansk, DTU.dk, Index, Contact, Phonebook, DTU Alumni, Portalen, and About this website. The main header identifies the center as 'Risø DTU National Laboratory for Sustainable Energy' and 'Technical University of Denmark DTU'. A secondary navigation bar lists Research, Education, Business Relations, Meet us, Job and Career, News and Calendar, Knowledge Base, and About Risø DTU. Below this, a sub-navigation bar highlights Sustainable energy, Nuclear technologies, and Centres. The main content area features a 'Welcome' sidebar with links to Services, Brochure, and Contact. The central text introduces the FCH Test Center, established in 2010 at Risø DTU, and lists its services: Testing, Training, Consultancy, and Certification. It also describes the center's role in providing large-scale advanced testing and demonstration of components and systems. A section titled 'The technologies and applications in focus are:' lists Fuel cells and electrolysis, SOFC, PEM, HT-PEM and DMFC, and Micro-CHP, APU, UPS and power train. The page includes images of laboratory equipment and a contact box for Eva Ravn Nielsen, Center Manager. The footer mentions collaboration with DGC and funding by EUDP (Energiteknologisk udvikling og demonstration). The page is updated by Heidi Adler Pedersen on 15.07.2011.

Milestone 1.1 III

Activity/Milestone

1.1 Market introduction and marketing of the Center

III) Presentation Danish industry

The partners of the test center project participated in the Annual Assembly of the Partnership for Hydrogen and Fuel Cells in April 2010 and presented the center:

Test and Approval Center for Fuel Cell and Hydrogen Technologies

Anke Hagen
Head of Programme
Fuel Cells and Solid State Chemistry Division

April, 19, 2010



$$f(x+\Delta x) = \sum_{i=0}^{\infty} \frac{(\Delta x)^i}{i!} f^{(i)}(x)$$

INTELLIGENT GAS TECHNOLOGY **DGC**

Risø DTU
National Laboratory for Sustainable Energy

Milestone 1.1 IV

Activity/Milestone

1.1 Market introduction and marketing of the Center

IV) Press mention

The Test center was presented in an article in FiB - Forskning i Bioenergi, Brint & Brændselsceller in June 2012:

Link to article:

http://www.biopress.dk/PDF/FiB_40-2012_06.pdf

Front of article:

Brint • Brændselsceller

Testcenter med fokus på elektrolyse



Testcentret for brint og brændselsceller er blevet en central spiller, når det handler om at koordinere projekter inden for elektrolyse. DTU Energikonvertering, som centret hører under, var i maj vært for et international elektrolysesymposium, og centret er på det seneste blevet engageret i en række projekter, hvor overskydende vindmøllestrøm skal lagres i form af brint.

Af Torben Skott

Med vedtagelsen af det seneste energiforlig er der for alvor kommet fokus på, hvordan vi skaber balance i et energisystem, der i stigende grad bliver baseret på vedvarende energi. Allerede i 2020 skal 35 procent af Danmarks energiforsyning stamme fra sol, vind og biomasse, og knap halvdelen af elforsyningen skal på det tidspunkt være baseret på vindkraft. Der er således et akut behov for at få kommercialiseret de teknologier, der kan lagre vinderenergien til vindstille perioder, og det har fået det kun to år gamle testcenter for brint og brændselsceller på DTU Energikonvertering til at sætte fokus på brintfremstilling via elektrolyse.

– Brint bliver et vigtigt medie for energilagring. Batterier kan fungere som lager i nogle få minutter, men kan lagres i natargasnettet i flere måneder, forklarer Eva Ravn Nielsen der er leder af testcentret for brint og brændselsceller, også kaldet FCH Test Center. Det står for Fuel Cell and Hydrogen technologies.

FCH Test Center blev etableret i 2010 af det daværende Risø DTU og Dansk Gasteknisk Center. Det skete med en to-årig bevilling fra EUDP på fem millioner kroner, der udløber den 1. juli i år. Det betyder, at centret nu skal til at stå på egne ben, og det har gjort det nødvendigt at udvide aktiviteterne til ikke kun at omfatte afprøvning af brint og brændselscellesystemer.

Elektrolyse er tæt på markedet

– Vi vil rigtig gerne teste fabrikanternes anlæg, men på nuværende tidspunkt er der ikke tilstrækkeligt med skæftige to faste medarbejdere og 4-5 tilknyttede forskere. Teknologien er endnu for langt fra et kommercielt gennembrud, og test- demonstrationprojekter er derfor en væsentlig del af aktiviteterne, siger Eva Ravn Nielsen.

FCH Test Center er i dag engageret i fem projekter om brint og brændselsceller, hvoraf tre af projekterne har fokus på elektrolyse. Det drejer sig dels om et projekt om etablering af elektrolyseanlæg i København, udvikling og afprøvning af elektrolyseteknologier til havbaserede vindmøller og bølgekraftanlæg samt det såkaldte HyProvide, hvor FCH Test Center skal koordinere en række danske elektrolyseprojekter.

– Vi havde ikke forudsat for et år siden, at hovedparten af vores aktiviteter ville blive koncentreret om elektrolyse, siger forsker Beng Ny-

14 | FiB nr. 40 • juni 2012

Milestone 1.1 V

Activity/Milestone

1.1 Market introduction and marketing of the Center

V) Presentation of center at an international conference

Centeret blev præsenteret ved diverse konferencer og udstillinger vha. flyer og desuden med en eller flere slides som del af faglige eller oversigtsforedrag (se figur), f.eks. til Hannover Messen i Tyskland og SOFC Konferencen i Montreal.

FCH Test Center

Fuel Cell and Hydrogen Technologies

- ❑ Will give industry access to large-scale advanced testing and demonstration of components and systems, standardization, consultancy, education, etc. to support the transition from R&D to the commercial break through



In cooperation with



Risø DTU
National Laboratory
for Sustainable Energy



And the companies



GREENHYDROGEN.DK



Milestone 1.2 I

Activity/Milestone

1.2 Establishment of an Advisory board & start of interaction with Center; networking with industrial players and relevant international institutions

I) Decision about participants

In the application for the project, the necessity of a close follow up on industry needs and current trends was pointed out as key factor for the successful establishment and development of the Test Center. An Advisory board comprising of key players such as members of industry, authority representatives and representatives of the Partnership for Hydrogen and Fuel Cells was seen a guarantee to fulfill this ambition.

The main tasks for the Advisory board were defined as:

- Exchange of information and knowledge
- Identification of needs and options
- Feedback on the plans to further develop the Test Center

According to these tasks, the following participants were selected:

Topsoe Fuel Cells	Rasmus Barfod
Dantherm Power	Martin Grøn
H2 Logic	Michael Sloth
IRD Fuel Cells	Laila Grahl-Madsen
Serenergy	Mads Bang
Danish Power System	Hans Aage Hjuler
Partnerskabet for brint og brændselsceller	Aksel Mortensgaard
Energistyrelsen	Anne Nielsen
Sikkerhedsstyrelsen	Carsten Sørig

Milestone 1.2 II

Activity/Milestone

1.2 Establishment of an Advisory board & start of interaction with Center; networking with industrial players and relevant international institutions

II) Kick-off meeting

The Kick-off meeting with the Advisory Board was held in Nyborg Strand, 23. June 2010, with good participation and intensive and fruitful discussions.

Participants:

Rasmus Barfod, Topsoe Fuel Cells

Martin Grøn, Dantherm Power

Hans Aage Hjuler, Danish Power Systems

Rasmus Munksgård Nielsen, IRD Fuel Cells

Aksel Mortensgaard, Partnerskabet for brint og brændselsceller

Anne Nielsen, Energistyrelsen

Jan K. Jensen, Dansk Gasteknisk Center

Eva Ravn Nielsen, Risø DTU

Anke Hagen, Risø DTU

Trygve Kalf Hansen, Risø Innovations Aktiviteter

Birna S. Colbe Månsson, Risø DTU

Agenda:

10.00	Velkomst og præsentation af deltagere	Eva Ravn Nielsen
10.20	Orientering om centeret. Præsentation af vision, status og planer for testcenteret	Eva Ravn Nielsen
10.40	Præsentation af centerets ydelser. Oplæg og diskussion Er det de rigtige ydelser Risø DTU og DGC tilbyder? - Hvilke andre ydelser efterspørges? - Er der behov for yderligere parter i centeret for at dække ydelsesområdet? - Hvad er det forventede omfang frem til 2015? - På hvilke økonomiske vilkår kan centerets ydelser leveres?	Eva Ravn Nielsen. Ordstyrer: Trygve Kalf Hansen
12.00	Frokost	
13.00	Foreløbige planer for ansøgning til Green Labs DK - Gennemgang af interessetilkendegivelse - Forslag og kommentarer fra Advisory Board	Eva Ravn Nielsen. Ordstyrer: Anke Hagen
14.00	Advisory Boards rolle nu og i fremtiden. Oplæg og diskussion - Sammensætningen af Advisory Board - Er der flere deltagere, vi kan have glæde af?	Jan K. Jensen
14.30	Opsummering af dagen	Eva Ravn Nielsen
14.45	Kaffe, kage og mulighed for netværk	

Milestone 1.3a I

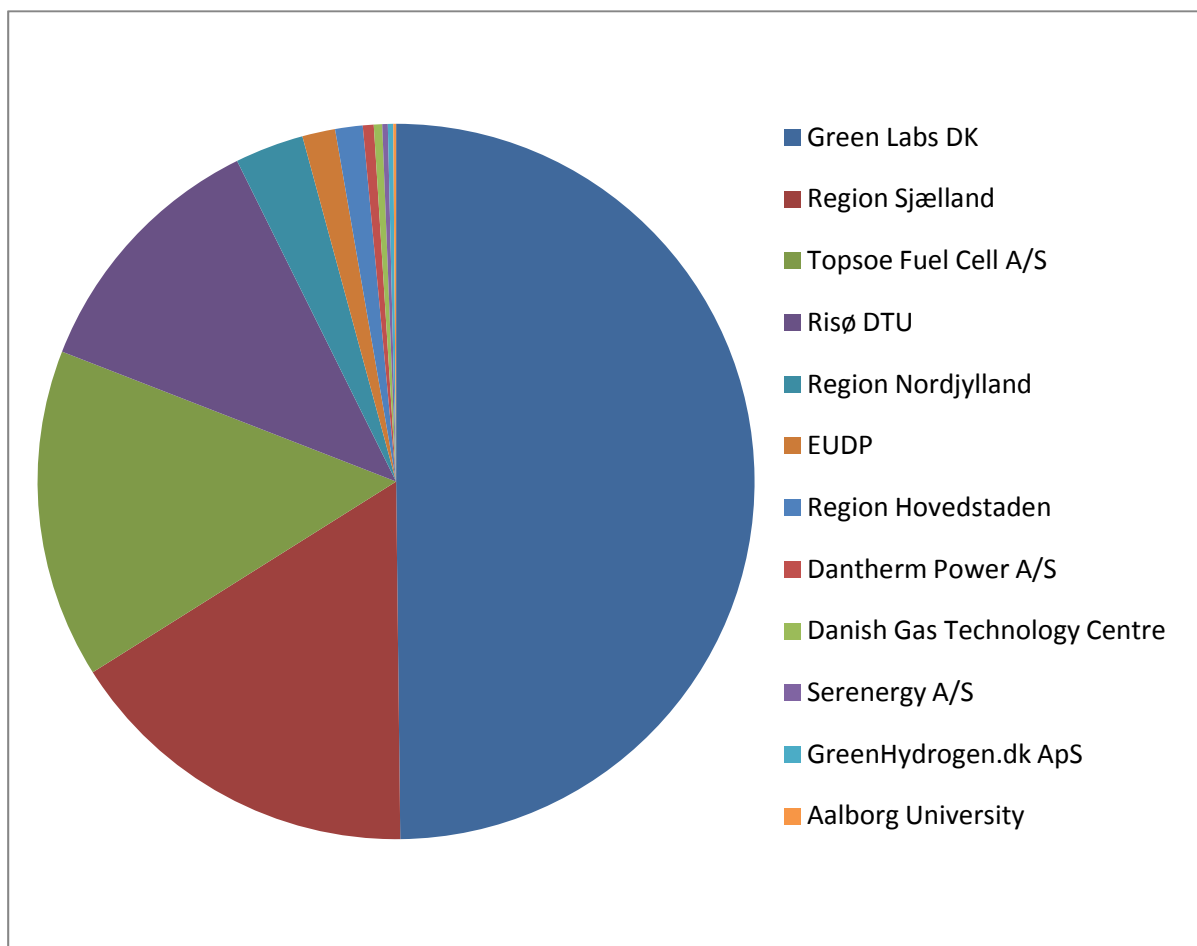
Activity/Milestone

1.3a Preparation and start of phase II, (def. of & application for projects)

I) *Preliminary* financing plan for center

Large, successful effort was spent to achieve co-financing for the further establishment and running of the center by contacting industry and sponsors and receive their commitment. A plan was established to provide financing for the further establishment of the center including public, commune and private sources and was included in the GreenLabs application.

Distribution of financing for establishment of center based on a total budget of 80,7 mio. DKK within the GreenLabs application:



Milestone 1.3a II

Activity/Milestone

1.3a Preparation and start of phase II, (def. of & application for projects)

II) Application of Green Lab DK

A comprehensive application was submitted. Large effort was spent to provide marketing plan, analysis of competitors, market analysis, realistic business plan, etc. Later, the application was thoroughly revised to meet the new requirements specified by the EU/energinet.dk. We successfully integrated all main Danish players in the concept.

Front page of GreenLabs application:

Green Lab for Fuel Cells and Hydrogen: “Risø FCH Test Center”



Risø DTU
National Laboratory
for Sustainable Energy



in cooperation with



and the companies



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Milestone 1.3a III

Activity/Milestone

1.3a Preparation and start of phase II, (def. of & application for projects)
--

III) Application of appropriate projects
--

Vi har løbende analyseret situationen i industrien og kontaktet mulige nye samarbejdspartnere både nationalt og internationalt, såvel bland forskningsinstitutter som industri, mhp. at søge relevante projekter.

Følgende projekter med involvering af Testcenteret blev søgt eller startet i 2011:

- **H2Ocean**-projektet (EU, 7. Rammeprogram, Koordinator: Meteosim Truewind S.L., Spanien)

Status: Startet

- **ene.field** JTI-projekt (EU, 7. Rammeprogram, Koordinator: COGEN Europe, Belgien)

Status: Godkendt. Forhandling i gang.

- **STACK-TEST** JTI-projekt (EU, 7. Rammeprogram, Koordinator: ZSW, Tyskland)

Status: Godkendt. Invitation til forhandling.

- **HyProvide** koordinering (Koordinator: Partnerskabet for Brint og Brændselsceller)

Status: Godkendt.

Milestone 1.3a IV

Activity/Milestone

1.3a Preparation and start of phase II, (def. of & application for projects)

IV) Financing of phase II secured by appropriate applications

The continuation and further development of the test center is financially secured by a number of projects:

Funded projects	Commissioned work	Technologies
2010 Test Center Initiation (EUDP)	First offers (corrosion) (B)	SOFC and general Standardisation Component testing
2011	First order (DK) Contract (USA)	SOFC, mech. testing Cells, stacks Batteries
2012 H2Ocean (EU) HyProvide coordination (EUDP) Ene.field (EU) Stack Test (EU)	Orders... S, DK, D, ...	Component testing Cells, stacks Electrolysis PEM μ -CHP Standardisation Authority handling Analysis Project coordination
2013 (to be applied for) Smart Copenhagen (EUDP) Power Core Testing (EUDP)		Semi-systems (HotBoxes) Electrolysis

Milestone 1.4 I

Activity/Milestone

1.4 Finalizing of road maps for the Center development

I) Proposal roadmap

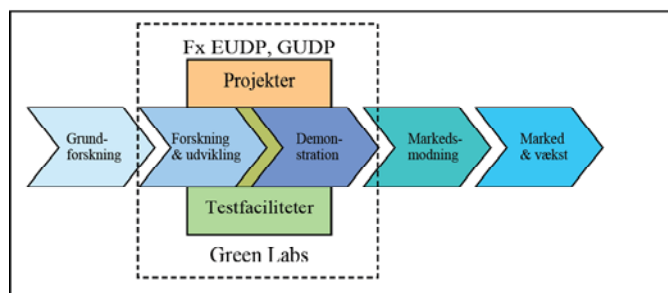
The roadmap for the development of the testcenter was presented at the General Assembly of the Partnership for Hydrogen and Fuel Cells in 2010.

Phase I (2010-2011): Initialization of the Center (EUDP, 5 mill. DKK, 2010-2012):

- Start-up and marketing of the Center
- Establishment of first activities:
 - Development, performance, and standardization of accelerated testing of fuel cells / systems
 - Advising on standardization
 - Networking with industrial players and international institutions
 - Finalizing road maps for the Center development
 - Preparation and fund raising for further establishment of center

Phase II (2010-2013): Further establishment of Center:

- Marketing, networking, business model, project applications, follow-up on industry status
- Extension of activities:
 - Acquisition of test capacity, comprehensive test campaigns
 - Development of fuel cell testing and characterization methodology (e.g., mechanical robustness, structural integrity)
 - Test of hydrogen components
 - Standards, regulations, safety and handling issues
 - Education on different levels (university, technical schools, etc.) to establish a comprehensive knowledge base regarding system installation, operation and maintenance services
- GreenLabs Application: Investments in the range of 70-80 mill DKK
 - Acquisition of facilities and installation of necessary infra structure (building, gas supply, etc.)
 - Acquisition of test stations
 - Installation of test stations



Phase III (2013-2016): Further development of Center:

- Definition and prioritizing of future activities based on the present situation at that time
- Development of new competences to be able to offer required services in the future
- Higher degree of internationalization in regard to international industry customers
- Extension of activities

Milestone 1.4 II

Activity/Milestone

1.4 Finalizing of road maps for the Center development

II) Revised roadmap

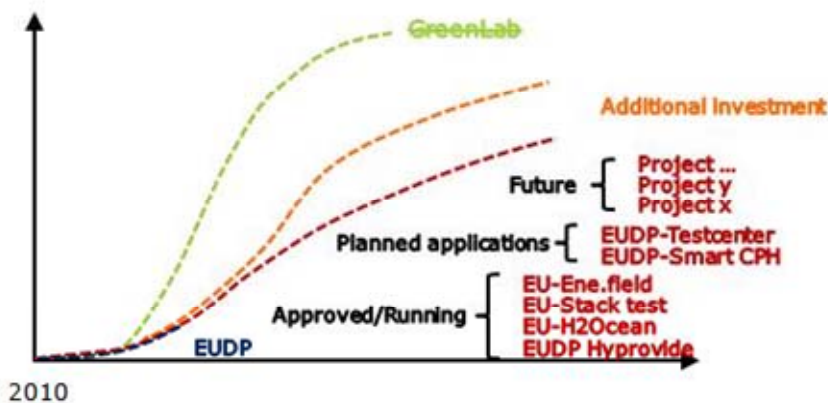
The continuation of FCH Test Center (phase 2) is secured by a number of projects (see milestone report 1.3a IV)). More projects are planned in the future. Commissioned work is expected to play a growing role of the FCH Test Center economy.

Investments in test equipment to achieve the required test capacity is still uncertain. Some equipment may be financed through projects, but only to a small extent. Also investments may be needed for expansion of laboratory space for the test equipment. There is at the moment no plan for these investments, but various possibilities are being examined and pursued on a preliminary level.

Base on an updated SWOT analysis:

	Helpful to achieving the objective	Harmful to achieving the objective
Internal origin attributes to the organisation	<ul style="list-style-type: none"> • Strong branding world-wide, professional, trustworthy, strong competences, neutral, independent • Strong network, in Denmark, in particular • Desired and involved in many national and international projects • Broad & strong research base (Department) and flexible use of facilities, manpower and knowhow • First mover (electrolysis) 	<ul style="list-style-type: none"> • Missing list of references (what value for money) • Uncertainty about own strategy • Low risk acceptance, heavy organisation (how can urgent industry requests be tackled)
External origin attributes to the environment	<ul style="list-style-type: none"> • Hydrogen and fuel cells are progressing and get political support, world-wide • Available facilities at Risø and Lyngby Campus • No existing test center for electrolysis yet • Synergies with Demonstratorium & Risø Forskerpark • Demonstration aspect • Upscaling from cells to stacks, modules & systems 	<ul style="list-style-type: none"> • Uncertain timeline when the technologies finally enter the market • Young industry with frequently changing strategies & needs • Young industry with no up-front money to pay (often projects needed, often can money only be spent nationally) • Uncertain specifications for certification, and if/which accreditation will be required

The expected further development of the test center is illustrated here:



Milestone 2.1 I

Activity/Milestone
2.1 Installation, development and performance of accelerated life-time tests of fuel cell systems
I) Project outline defined

Development of accelerated SOFC test

Initial part of the outline:

In this project task, an accelerated test protocol for testing of single cell stacks aiming at supporting the evaluation of life time of SOFCs by determining acceleration factors will be developed. Accelerating parameter will be power density (current load). The single cell stack tests will be carried out in parallel to tests of larger stacks. The tests are aiming at the μ -CHP market.

Looking at the μ -CHP market, current load (or power output) is a relevant parameter that is varied periodically in the range of minutes and hours over a day. Changes of the power output are known to cause thermal effects (temperature differences, gradients), which in turn can lead to accelerated de-gradation or even hard failure (mechanical failures of cells, mechanical cell integrity, loss of contact in the stack, hot spots, etc.).

The acceleration factor will be determined for tests under rapid cycling of the current load compared to either constant conditions or 'normal' load profiles. Apart from the current load, also the temperature could be an interesting parameter to include in accelerated testing (e.g. corresponding to sudden shut down of the SOFC). However, as the stacks exhibit a considerable thermal mass, which slows down cooling of the system, a fast thermal cycling is not as relevant at this point.

Milestone 2.1 II

Activity/Milestone

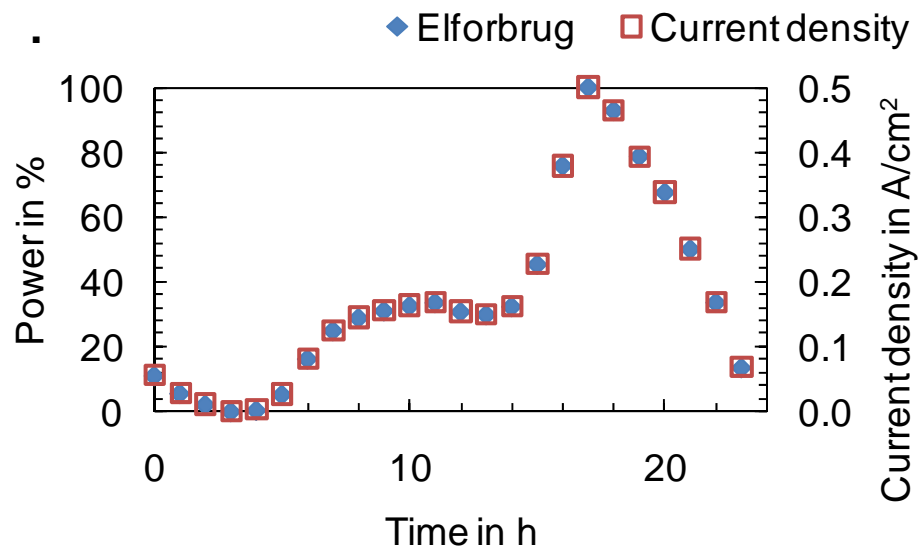
2.1 Installation, development and performance of accelerated life-time tests of fuel cell systems

II) Accelerated test procedure **proposed**

Originally, an accelerated test procedure should have been defined by this time. However, it has not yet been possible to start the actual testing, as the test rig was not operational due to required substantial installation efforts. Therefore, the current procedure is a proposal until it has been tested and verified.

As outlined in the task to develop an accelerated test protocol, the aim is to vary (cycle) the power density, i.e. current load over time, corresponding to a user profile of a real application. Data collected for the electricity use of one family houses were analysed and a profile was deduced that can be applied in our test facilities.

Example for initial accelerated test profile to be applied to single cell stacks and stacks, based on measured electricity use of one-family houses. This profile will be applied to single cell stacks and larger stacks with increasing frequency depending on the obtained results (i.e. one cycle per day, 5 cycles per day, 10 cycles per day, etc.):



Milestone 2.1 III

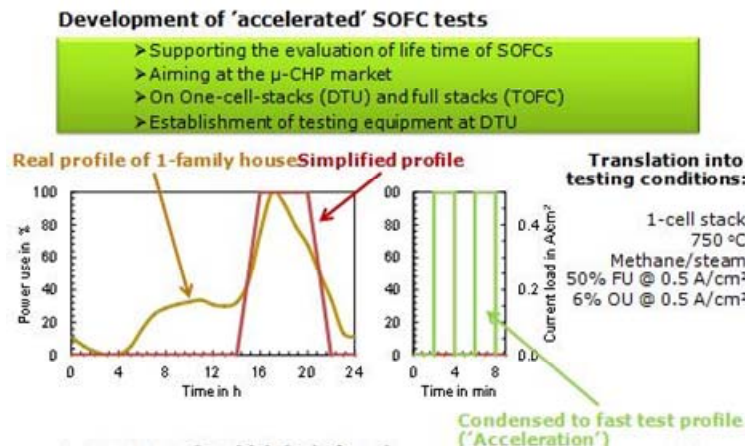
Activity/Milestone

2.1 Installation, development and performance of accelerated life-time tests of fuel cell systems

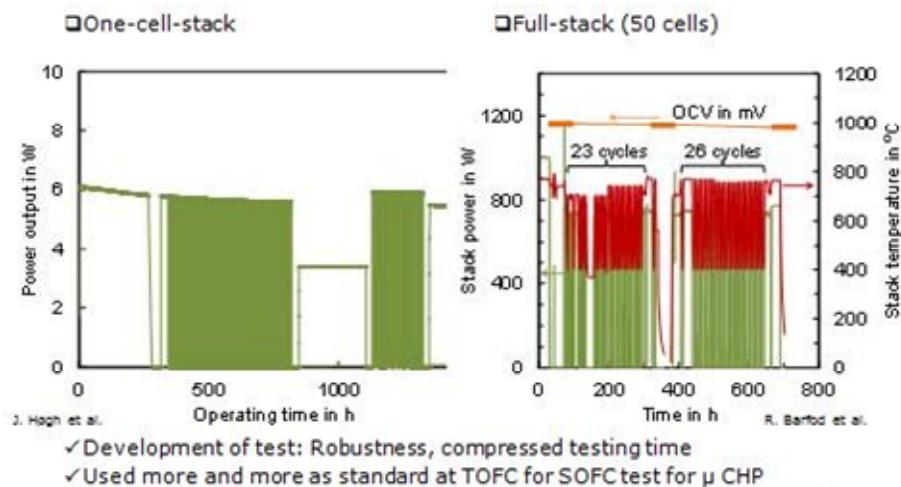
III) Accelerated test procedure defined

Based on the originally proposed test procedure a number of modifications were made. The aim was to compress the tests, to achieve durability results in shorter times. A more rapid power output cycling was programmed (within few minutes) instead of the one cycle per day, as expected in real life. In that way, the number of power cycles expected for the whole life time of the SOFC unit, can be executed within a few 100 to 1000 hours and can be used as robustness tests for SOFC stacks. The testing protocol was applied to one-cell-stack at DTU and in modified version on 50-cell-stacks at TOFC.

Theoretic test profile:



Examples for executed tests:



Milestone 2.2 I

Activity/Milestone

2.2 Standardisation issues of accelerated fuel cell testing

I) Report of standardisation pre-survey

A survey was made by DGC addressing worldwide players and status in the field of accelerated tests of SOFCs. The content of the survey is shown below:

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Milestone 2.2 II & III

Activity/Milestone

2.2 Standardisation issues of accelerated fuel cell testing

II) Meeting of interest group for standard development

III) Formulation discussion basis

Et fælles diskussionsoplæg (Risø, DGC, TOFC) blev udarbejdet og præsenteret ved Degraderingsworkshop i Grækenland i september 2011 (se figur med titel for præsentationen), med relevante deltagere fra industri og forskning fra hele verden. Den efterfølgende diskussion viste en bred enighed om nødvendighed for accelererede test og en harmonisering / standardisering af test. Vores projekt med at arbejde på en testprotokol for levetidstest blev modtaget positivt og betydningen blev understreget. Der var dog ikke tilstrækkelig engagement på nuværende tidspunkt at indgå eller deltage i mere forpligtende projekter eller diskussionsgrupper på tværs af organisationer/lande.

Konklusionen fra workshop er, at vi fortsætter med at udvikle testproceduren og prøver at tage standardisering op ved senere tidspunkt, f.eks. i forbindelse med nye EU-calls.



Assessing durability of SOFC stacks

Anke Hagen

Head of Programme

Fuel Cells and Solid State Chemistry Division

Risø DTU

Rasmus Barfod

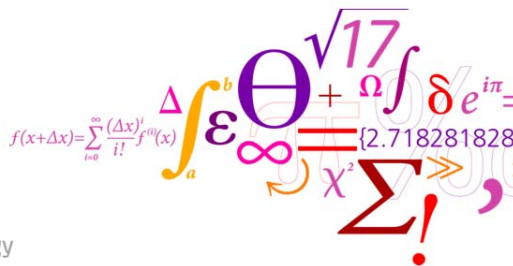
Topsoe Fuel Cell

Mikael Näslund, Henrik Iskov

Danish Gas Technology Centre

Risø DTU

National Laboratory for Sustainable Energy



Milestone 2.3 I

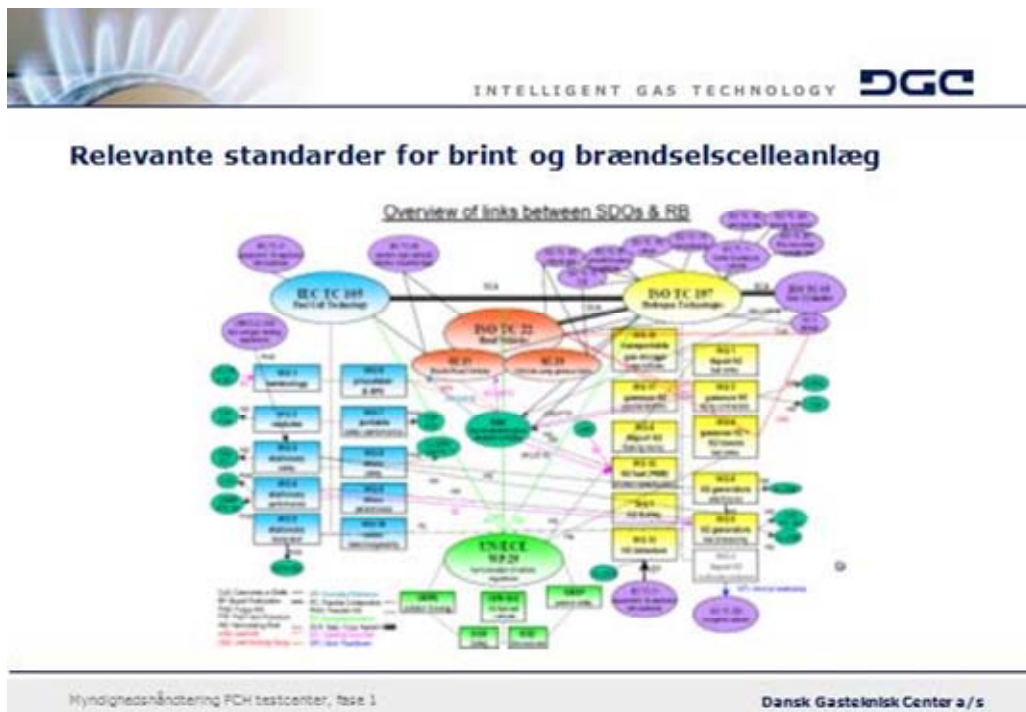
Activity/Milestone

2.3 Consultancy in relation to certification & approval

I) Instruction guidelines for handling with authorities in the fuel cells & hydrogen area outside the process industry in Denmark

The guidelines were formulated.

Clip of the document:



Dissemination

There has been focus on dissemination on different levels, both general information about the project and the test center, and also scientific communication of the project results to the scientific and/or industrial audience.

Public and broader information about the test center and the project

A Brochure about the test center was designed, continually updated, and distributed for example at the Hannover Messe in 2011 og 2012, the international *SOFC-XII* conference in Montreal in 2011, and the conference *European Fuel Cell Forum* in Lucerne in 2012.

Link:

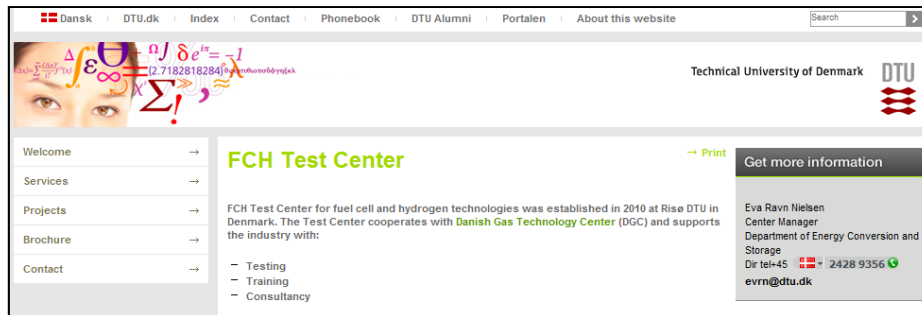
http://www.energyconversion.dtu.dk/sitecore/content/Campus/Home/Research/sustainable_energy/fuel_cells/projects/FCH_Test_center/~/_media/Risoe_dk/Research/FCH_test_center/Documents/2012-04-19%20Brochure%20low%20res.ashx

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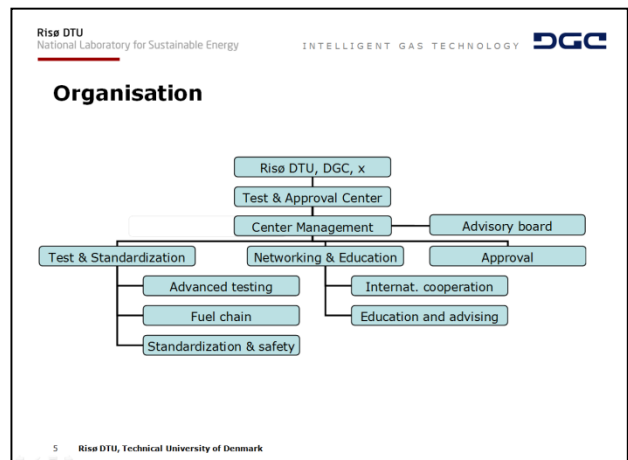
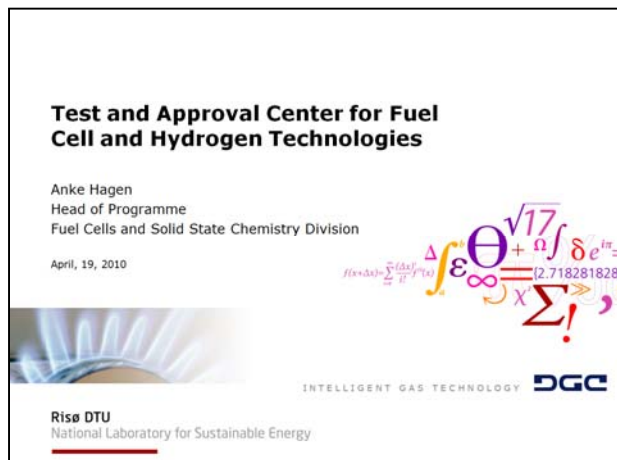


Home page:

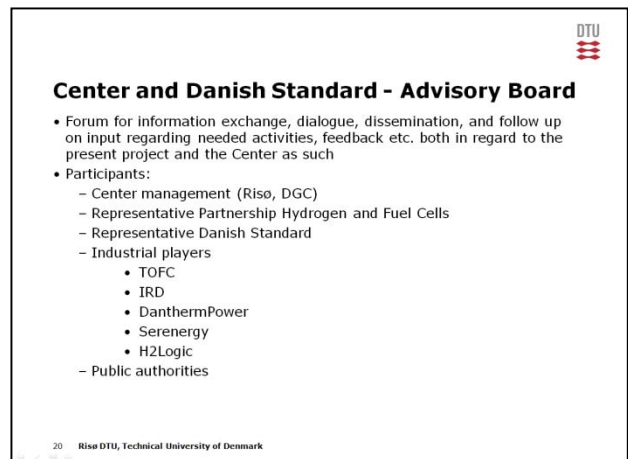
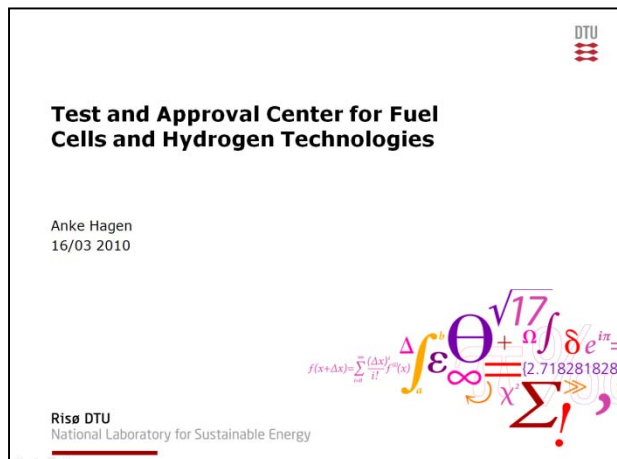
www.fch.dk



The project and test center was presented at the General Assembly of the Partnership for Hydrogen and Fuel Cells in 2010:



The test center was presented at the meeting of *Dansk Standard* in 2010:



The test center was presented to the Minister of Energy, Lykke Friis, during a visit organized by the Partnership for Hydrogen and Fuel Cells in 2010:

Test- og godkendelsescenter for brændselscelle- og brintteknologier

Eva Ravn Nielsen
25. juni 2010



INTELLIGENT GAS TECHNOLOGY **DGC**

Risø DTU
Nationallaboratoriet for Bæredygtig Energi

DGC


Center of Excellence

- Vi vil være det foretrukne europæiske testcenter inden for brændselscelle- og brintteknologier.
- Danmark er det første land, der opretter et center af denne type.
- Vi kan lægge os i front og skabe et "center of excellence".
- Vi bygger på internationalt respekterede danske styrkepositioner på områderne.
- Et videncenter, hvor industri, forskning og myndigheder deler viden og bygger på hinandens viden.
- Attraktivt for udenlandske spillere at slå sig ned i Danmark.

⇒ **Det danske brændselscelle-eventyr**


- Skabe eksport og arbejdspladser.

A poster with general information about electrolysis activities in the test center was presented at the workshop: *Water electrolysis and hydrogen as part of the future Renewable Energy System*, in Copenhagen in 2012.



Electrolysis activities at FCH Test Center


Eva Ravn Nielsen and Frederik Berg Nygaard



FCH Test Center

DTU Energy Conversion





Scientific contributions with activities and results from the project

At the *2nd Workshop on Degradation Issues for Fuel Cells* in Greece, in September 2011, the outcome of the analysis of activities on accelerated and compressed testing and considerations on compressed testing for SOFC for use in μ CHP was presented. A discussion about international harmonization of SOFC testing in this regard was initiated.

DTU


Assessing durability of SOFC stacks

Anke Hagen
Head of Programme
Fuel Cells and Solid State Chemistry Division
Risø DTU

Rasmus Barfod
Topsoe Fuel Cell

Mikael Näsrlund, Henrik Iskov
Danish Gas Technology Centre

Risø DTU
National Laboratory for Sustainable Energy




DTU

Risø DTU
National Laboratory for Sustainable Energy

Acknowledgements

We gratefully acknowledge support from :

- Danish Energy Authority 

In the frame of the project:

- Test Center for Fuel Cell and Hydrogen Technologies. Phase 1. (EUDP 09-II)

12 Risø DTU, Technical University of Denmark 2nd Int. Workshop on Degradation Issues of Fuel Cells, Thessaloniki, 2011

Results from compressed SOFC stack testing within the frame of the project were presented at the *10th International Symposium on Ceramic Materials and Components for Energy and Environmental Applications* in Germany in May 2012:

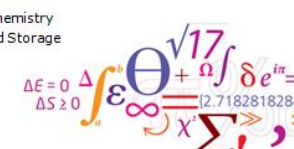
DTU

SOFC Durability under Realistic Operation

Anke Hagen

Head of Program for Applied Electrochemistry
Department of Energy Conversion and Storage
(former Risø)







DTU Energy Conversion
Department of Energy Conversion and Storage



DTU

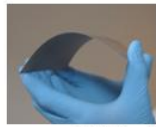
Acknowledgements

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- Topsoe Fuel Cell A/S 
- Danish Energy Authority 
- Energinet.dk 
- EU Framework Programmes 
- Danish National Advanced Technology Foundation 
- Danish Research Councils
- DONG Energy 

DTU Energy Conversion, Technical University of Denmark

Anke Hagen 10th CHCC

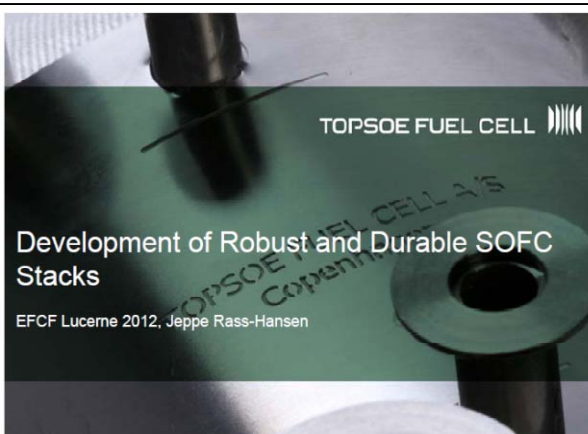


Full stack test results on compressed testing from the project were presented at the European Fuel Cell Forum in Lucerne in June 2012:

TOPSOE FUEL CELL

Development of Robust and Durable SOFC Stacks


EFCF Lucerne 2012, Jeppe Rass-Hansen



TOPSOE FUEL CELL

For further information
Please contact Rasmus G. Barfod
raba@topsoe.dk

Thanks for your attention

FCH Test Center
funded by 

Rasmus G. Barfod
Kresten Juel Jensen
Thomas Heiredal-Clausen
Jeppe Rass-Hansen

Jeppe Rass-Hansen, Lucerne 2012

Danish Press

The test center was devoted an article in FIB (Forskning i Bioenergi, Brint & Brændselsceller) in June 2012.

Link: http://www.biopress.dk/PDF/FiB_40-2012_06.pdf

First page:

Brint • Brændselsceller

Testcenter med fokus på elektrolyse



Testcentret for brint og brændselsceller er blevet en central spiller, når det handler om at koordinere projekter inden for elektrolyse. DTU Energikonvertering, som centret hører under, var i maj vært for et internationalt elektrolysesymposium, og centret er på det seneste blevet engageret i en række projekter, hvor overskydende vindmøllestrøm skal lagres i form af brint.

Af Torben Skætt

Med vedtagelsen af det seneste energilov er der for alvor kommet fokus på, hvordan vi skaber balance i et energisystem, der i stigende grad bliver baseret på vedvarende energi. Allerede i 2020 skal 35 procent af Danmarks energiforsyning stamme fra sol, vind og biomasse, og knap halvdelen af elforsyningen skal på det tidspunkt være baseret på vindkraft. Der er således et akut behov for at få kommercialiseret de teknologier, der kan lagre vindenergien til vindstille perioder, og det har fået det kun to år gamle testcenter for brint og brændselsceller på DTU Energikonvertering til at sætte fokus på brede fremstilling via elektrolyse.

— Brint bliver et vigtigt medie for energilagring. Batterier kan fungere som lager i nogle få timer, men brint kan lagres i natursgasnettet i flere måneder, forklarer Eva Ravn Nielsen der er leder af testcentret for brint og brændselsceller, også kaldet FCH Test Center. Det står for Fuel Cell and Hydrogen technologies.

FCH Test Center blev etableret i 2010 af det daværende Risø DTU og Dansk Gasteknik Center. Det skete med en to-årig bevilling fra EUOP på fem millioner kroner, der udløber den 1. juli i år. Det betyder, at centret nu skal til at stå på egne ben, og det har gjort det nødvendigt at udvide aktiviteterne til ikke kun at omfatte afprøvning af brint og brændselscellesystemer.

Elektrolyse er tæt på markedet

— Vi vil rigtig gerne teste fabrikantens anlæg, men på nuværende tidspunkt er der ikke tilstrækkeligt med kommercielle opgaver til at kunne beskæftige to faste medarbejdere og 4-5 tilknyttede forskere. Teknologien er endnu for lang fra et kommercielt gennembrud, og test- og demonstrationsprojekter er derfor en væsentlig del af aktiviteterne, siger Eva Ravn Nielsen.

FCH Test Center er i dag engageret i fem projekter om brint og brændselsceller, heraf tre af projekterne har fokus på elektrolyse. Det drejer sig dels om et projekt om etablering af elektrolyseanlæg i København, udvikling og afprøvning af elektrolyseanlæg til håndterende vindmøller og bølgekraftanlæg samt det såkaldte Hylhede, hvor FCH Test Center skal koordinere en række danske elektrolyseprojekter.

— Vi harde ikke forudset for et år siden, at hovedparten af vores aktiviteter ville blive koncentreret om elektrolyse, siger Frederik Berg Ny-

Another article was submitted to FIB about the project and is expected to be published in one of the next issues.

Submission:

EUDP - FCH Test Center Fase 1

Journalnr.: 64009-246

Projekt over 8,9 mio kr., med DTU Energikonvertering (tidligere Risø DTU) som projektleder og Dansk Gasteknik Center og Topsoe Fuel Cell som partnere. Start 1.1.2010 slut 30.6.2012

Projektet havde to hovedmål: at opstarte et Test- og Godkendelsescenter for brændselscelle- og brintteknologier og at starte med første aktiviteter på accelererede levetidstest af højtemperaturbrændselsceller (SOFC). I løbet af projektet blev navnet FCH Test Center valgt.

Det lykkedes ved aktiv indsats at etablere et stort nationalt og internationalt netværk med vigtige spillere fra industrien og forskningsverdenen, f.eks. medlemmer af Partnerskabet for Brint og Brændselsceller, tysk elektrolysevirksomhed Sunfire, australsk/tysk brændselscellevirksomhed CFCL og et nordiske netværk af testcentre. FCH Test Center er blevet kendt og efterfølgende inviteret til at deltage i store internationale projekter. Her kan nævnes EU-projektet ene.field, som er et demonstrationsprojekt for mikrokraftvarme som samler alle de industrielle nøglespillere i Europa.

Testcenteret har fået en fremtrædende rolle som arbejdspladsleder. Andre nye projekter handler om elektrolyse og PEM-brændselsceller.

For at imødekomme industriens testbehov, er nyt testudstyr indkøbt og brugt til udvikling af accelererede levetidstest af SOFC celler og stakke, i tæt samarbejde med Topsoe Fuel Cell.

Dansk Gasteknik Center har gennemført standardiseringsaktiviteter og lavet forarbejde til at accelereret levetidstest af SOFC på sigt kan blive en international standard. Desuden har DGC udarbejdet en vejledning i myndighedshåndtering for stationære brint- og brændselscelleprojekter.

EUDP-projektet har været startskuddet for testcenteret. Efter projektets afslutning bærer nye projekter videre. De første kommercielle opgaver er kommet i hus, og det er fortsat ambitionen at blive det foretrukne testcenter for brændselsceller og brint i Europa for dermed at hjælpe industrien på markedet og styrke danske positioner på disse fremtidens teknologier. Mere kan læses på testcenterets hjemmeside: www.fch.dk.



Anke Hagen (Projektleder)
Eva Ravn Nielsen (Centerleder)



A F S L U T N I N G S - S K E M A

Dette skema udfyldes af projektansvarlige ved afslutning af EUDP-projekter. Informationerne i punkt 1 – 5 er beregnet til offentliggørelse og vil blive lagt ind i EUDPs projektportal på www.energitteknologi.dk.

Titel: EUDP-FCH Testcenter Fase 1 Journalnr.: 64009-246

Tilsagnshaver: DTU Energikonvertering Projektleder: Anke Hagen

1. Dansk resumé af projektets resultater. Sammenfat projektets resultater.
Hvilke teknologiske resultater er opnået? Hvorfor er de vigtige? Angiv nøgletal.

Projektets formål var at starte med et Test- og Godkendelsescenter for Brændselscelle- og Brintteknologier (arbejdspakke 1) og at påbegynde de første aktiviteter på udvikling af accelererede levetidstests af brændselscellesystemer, forberedelse for standardisering af disse metoder og rådgivning i forbindelse med certificering af brændselscellesystemer (arbejdspakke 2). Hovedresultater er:

Arbejdspakke 1:

- Et stort nationalt og internationalt netværk blev etableret, som omfatter vigtige industrielle spillere, forskningsinstitutioner og andre testcentre
- Det lykkedes at gøre testcenteret kendt i store dele af den internationale brændselscelle- og brintverden
- Et antal nye projekter med afgørende roller for testcenteret er blevet ansøgt og bevilliget, både nationalt og internationalt, som sikrer den videre etablering og udvikling af testcenteret

Arbejdspakke 2:

- Nyt udstyr til brændselscelletest blev installeret og taget i brug på DTU (Risø campus)
- En omfattende undersøgelse af internationale aktiviteter omkring accelereret levetidstest blev gennemført
- En testprotokol for højtemperaturbrændselscelletest med udgangspunkt i anvendelse på mikrokraftvarmeområdet blev udviklet og anvendt på enkeltcelle- og 50-cellestakke
- En vejledning for myndighedshåndtering blev formuleret

2. Energipolitiske mål. *Hvilke konsekvenser forventes projektet at få for CO₂-udledning, forsyningssikkerhed og uafhængighed af fossil energi? Kvantificér ud fra nøgletal pr. enhed og forventet salg.*

Centeret vil hjælpe indirekte med at opnå klima- og energipolitiske målsætninger, idet dets fokus er at bringe miljøvenlige teknologier tættere på markedet. Inden for projektets rammer handlede det om fastoxidbrændselsceller, hvor der foreligger en national strategi for at kommercialisere teknologien. Derudover har projektet været udgangspunkt for flere nye projekter, der også har aktiviteter på andre teknologier, der anses for at blive afgørende elementer i fremtidens energisystem baserende på vedvarende energikilder, f.eks. elektrolyse og lavtemperaturbrændselsceller.

3. Formidling. *Hvilke formidlingsaktiviteter har I gennemført? Angiv link eller henvis til offentliggjorte artikler og publikationer.*

Der har været adskillige formidlingsaktiviteter på forskellige niveauer med forskellige formål og målgrupper.

- Information om Testcenteret til bredt publikum, både nationalt og internationalt:
 - Home page: www.fch.dk
 - Informationsbrochure: http://www.energyconversion.dtu.dk/sitecore/content/Campus/Home/Research/sustainable_energy/fuel_cells/projects/FCH_Test_center/~/_media/Risoe_dk/Research/FCH_test_center/Documents/2012-04-19%20Brochure%20low%20res.ashx

Aktuelle udgaver af brochuren blev bl.a. fordelt ved Hannover Messen 2011 og 2012, den internationale SOFC-XII konference i Montreal i 2011 og konferencen *European Fuel Cell Forum* i Lucerne i 2012.

 - Poster ved Workshop: *Water electrolysis and hydrogen as part of the future Renewable Energy System*, Copenhagen, Maj 2012 (Eva Ravn Nielsen, Frederik Berg Nygaard)
 - Præsentation af projektet ved generalforsamlingen af Partnerskabet Brint og Brændselsceller i 2010 (Anke Hagen)
 - Præsentation af Testcenteret ved møde hos Dansk Standard i 2010 (Anke Hagen)
 - Indslag under et ministerbesøg af energiministeren Lykke Friis, organiseret igennem Partnerskabet for Brint og Brændselsceller i 2010 (Eva Ravn Nielsen)
- Bidrag til internationale videnskabelige konferencer og workshops med resultater fra projektet:
 - Præsentation ved *2nd Workshop on Degradation Issues for Fuel Cells*, Grækenland, September 2011
 - A. Hagen (DTU): *Assessing durability of SOFC stacks*
 - Præsentation ved *10th International Symposium on Ceramic Materials and Components for Energy and Environmental Applications*, Tyskland, Maj 2012
 - A. Hagen (DTU): *SOFC Durability under Realistic Operation*
 - Præsentation ved *European Fuel Cell Forum*, Schweiz, Juni 2012
 - Jeppe Rass-Hansen (TOFC): *Development of robust and durable SOFC stacks*

- Information i Dansk presse:
 - Artikel om Testcenteret i FIB (Forskning i Bioenergi, Brint & Brændselsceller), Juni 2012 (Torben Scott): Testcenter med Fokus på Elektrolyse: http://www.biopress.dk/PDF/FiB_40-2012_06.pdf
 - Artikel om det afsluttede projekt submitted til FIB

4. Engelsk resumé: *Sammenfat projektets resultater og læg vægt på de dele af projektet, som har særlig international interesse.*

The aim of the present project was to initialize a Test and Approval Center for Fuel Cell and Hydrogen Technologies at the sites of the project partners Risø DTU (Fuel Cells and Solid State Chemistry Division), and DGC (work package 1). The project furthermore included start-up of first activities with focus on the development of accelerated life-time tests of fuel cell systems, preparations for standardization of these methods, and advising in relation to certification and approval of fuel cell systems (work package 2). The main achievements of the project were:

Work package1:

- A large national and international network was established comprising of important commercial players, research institutions, and other test centers
- The test center is known in large part of the international Fuel Cell and Hydrogen community due to substantial efforts in 'marketing'
- New national and international projects have been successfully applied for, with significant roles of the test center, which secure the further establishment and development of the center

Work package2:

- Testing equipment was installed and commissioned at DTU (Risø Campus)
- A comprehensive survey among international players regarding activities on accelerated SOFC testing was carried out
- A test procedure for 'compressed' testing of SOFC in relation to μ CHP application was developed and used for one-cell stack and 50-cell-stack testing
- Guidelines for Danish authority handling were formulated

5. Finansiering. *Projektets finansiering fordelt på EUDP, egen- og andenfinansiering. Angiv faktiske beløb i 1.000 kr.*

Virksomhed/Institution	EUDP-tilskud	Projektdeltager	Anden finansiering	Totale udgifter
1 Risø DTU	3950	532	1720	6202
2 Dansk Gasteknisk Center DGC	1,020		1742	2762
3				0
4				0
5				0
6				0
7				0
8				0
9				0
10				0
I alt	4970	532	3462	8964

Tabellen aktiveres med dobbelt venstre klik. Lukkes med klik uden for tabellen.

6. Kommercielle resultater og perspektiver. *Forventes den udviklede teknologi markedsført? Hvornår? I hvilke lande? Har I opnået, eller forventer I at opnå, andre kommercielle resultater på baggrund af projektet? Hvilke?*

Et af testcenterets formål har været at udføre kommercielle test for virksomheder i brændselscelle- og brintindustrien for at fremme overgang fra forskning/udvikling til markedsgennembrud. Ved hjælp af projektet blev testcenterets etablering påbegyndt. Projektresultaterne (se afsnit 1) har lagt basis, at testcenterets første kommercielle aktiviteter, dvs. test for virksomheder, er kommet i gang. Igennem disse og testcenterets øvrige aktiviteter forventes det at hjælpe industrien på vej til markedet.

7. Næste skridt. *Hvad er næste skridt teknologisk? Og kommercielt? Forventer I at søge yderligere offentlig finansiering?*

Projektet har været startskud for testcenteret. Allerede inden for projektperioden blev der sat fokus på fortsat etablering og udvidelse ved at opbygge nationale og internationale konsortier og ved at søge projekter. Testcenteret har fået flere projekter med offentlig støtte. F.eks. handler et EU projekt med alle relevante europæiske spillere om demonstration af brændselsceller i mikrokraftvarme i hele Europa. Et Dansk projekt har til formål at koordinere elektrolyserelaterede projekter i Danmark. Derved har testcenteret en aktiv rolle i den videre teknologiudvikling og demonstration af brændselscelle- og brintteknologier.

8. Projektets betydning for indtjening og beskæftigelse

Projektdeltager (Skriv navn)	Antal ekstra medarbejdere i dag	Forventet antal ekstra medarbejdere indenfor 1-2 år	Forventet antal ekstra medarbejdere om 3 – 5 år
<i>DTU Energikonvertering</i>	3	2	4
Projektdeltager (skriv navn)	Omsætning i mio. kr i år	Forventet omsætning i løbet af 1 - 2 år	Forventet omsætning om 3 - 5 år
<i>DTU Energikonvertering</i>			

Appendix I:

Report: Accelerated lifetime testing and standardization of SOFC systems

Survey and test proposal

Appendix II: Report: Guidelines for authorities handling

Accelerated lifetime testing and standardization of SOFC systems

Survey and test proposal

Project Report

July 2012

Survey and test proposal

Mikael Näslund, Henrik Iskov

Danish Gas Technology Centre
Hørsholm 2012

Title : Accelerated lifetime testing and standardization of SOFC systems

Report

Category : Project Report

Author : Mikael Näslund, Henrik Iskov

Date of issue : 03-07-2012

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Appendices

A – Accelerated lifetime test of SOFC stacks. Prestudy – November 2010

B – Accelerated SOFC lifetime test procedures – April 2011

C – Test methods for assessing durability of SOFC stacks – March 2011

D – Test standard draft – SOFC lifetime prediction – September 2011

E – Assessing durability of SOFC stacks – September 2011

1 Introduction and results

There is a demand for methods to evaluate or predict the lifetime of SOFC systems. The mechanisms behind cell degradation are fairly well known, but the system aspects including the effects of operating conditions are less well known.

The project has shown that there exists no agreed method to predict the lifetime of an SOFC system. Even a lifetime definition does not exist. Investigations published in journals or at conferences often present a durability or degradation rate during steady-state or cycling operation. No attempt to use such experimental data to predict a lifetime in a general way has been observed.

The challenges found in developing tests and models for a lifetime prediction are:

- Lifetime definition, end-of-life (EOL)
- Shall tests of single stacks, short stacks, full stacks or full fuel cell system (cell stack, fuel processing and Balance of Plant (BoP)) be used for the lifetime prediction?
- Test program layout including load and temperature cycling
- Lifetime depends heavily on application, system sizing in relation to customer needs and actual operation. This again depends on local economic parameters such as fuel and electricity pricing (perhaps time-dependant) and taxation.

The first draft to a harmonised lifetime prediction method includes the following items:

- The system integrator predicts the lifetime based on stack tests.
- Stack tests are performed separately in steady state and cycling operation.
- Test results are presented in a way that different lifetime definitions are possible to use, taking into account the intended application and market for the SOFC system.
- The system integrator predicts the lifetime as a function of the upper and lower degradations rates, i.e. the steady state and cycling opera-

tion degradation. This function has to be developed based on estimates of the expected end-user operation of the system.

This method has been presented at the latest international degradation conference on PEM and SOFC fuel cells in order to find out if there was sufficient interest in harmonizing a method for accelerated lifetime testing of SOFC fuel cell systems.

2 Summary and conclusions

The development process of the draft standard for accelerated lifetime testing is described.

2.1 Identifying possible stakeholders for accelerated lifetime test of SOFC stacks.

As an initial task a worldwide survey of possible stakeholders for a new standard for accelerated testing of SOFC systems was performed. Further details can be found in Appendix A. The main reasons for such a standard are

- As lifetime of fuel-cell system are expected to increase to 50,000 to 80,000 hours (in order to compete with traditional solutions) the need for a standard for accelerated lifetime testing is strongly increased.
- A new standard for lifetime assessment will enable customers to compare the performance of different supplier systems and thereby facilitate international sales and marketing of fuel cell systems.

The possible stakeholders are identified as SOFC manufacturers, research organisations and developers.

The survey clearly shows the need for a standardized and harmonised test procedure. Lifetime data often lack description of the lifetime criteria and the operating conditions.

2.2 Literature review of durability and lifetime testing of SOFC systems

A review of all recent activities, papers and presentations from the stakeholders worldwide on the subject durability testing and accelerated lifetime testing has been performed. Details can be found in appendix B.

The report raises the following questions and focuses on the topics that have to be answered and discussed in the development of an accelerated test procedure.

- Definition of lifetime
- Preferred time for the lifetime tests and calculations
- Stack or system testing?
- The load pattern has to be determined
- How is acceleration achieved?
- Determination of acceleration factor

An example of the contents behind these topics is seen in Figure 1. The computer simulated operational pattern of a 1 kW micro cogeneration unit in a single family house is illustrated. The red areas show the fuel cell operation while the green lines show the electricity demand in the house. The left graphs show electricity controlled operation with a lot of load cycling. The graphs to the right show the operation in an application that is heat load controlled and surplus electricity can be exported to the grid. The fuel cell units operate in a steady state mode. This shows that the application is an important factor in the lifetime prediction model.

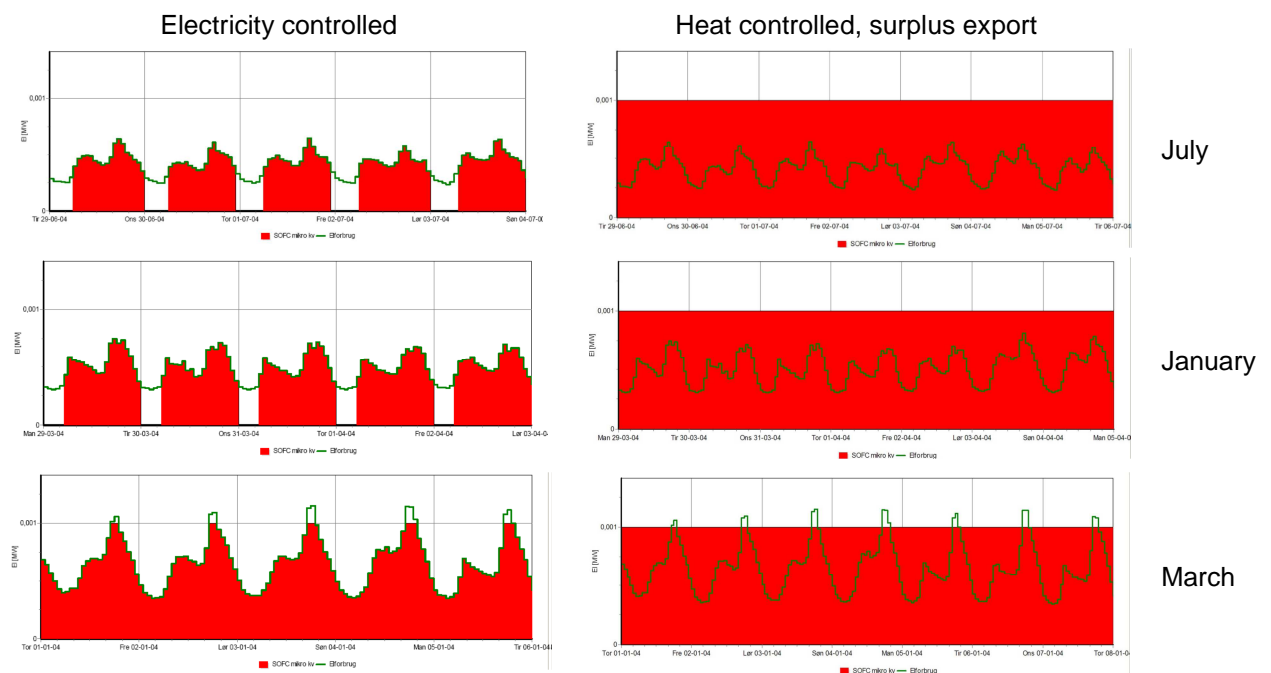


Figure 1 Calculated operational pattern for a micro cogeneration unit in a Danish single family house

2.3 Test method proposal from TOFC for assessing durability of SOFC stacks

Topsoe Fuel Cell (TOFC) proposes a test method to assess the durability of SOFC stacks. The proposal is based on TOFC comprehensive experience with testing SOFC systems. A test is suggested including 3000 hours of steady-state operation, and cycling operation including 200 load cycles and 25 thermal cycles. The durability is suggested to be reported as changes in area specific resistance, power density and cell voltage. All parameters are important for the lifetime prediction, but the proposal does not contain any methods to obtain an indication of actual lifetime of SOFC stacks.

Furthermore, the document states the way operating conditions shall be reported as well as defining the stack performance reporting structure. Further details can be found in appendix C.

2.4 Test standard discussion basis for SOFC lifetime prediction

Based on the TOFC proposal and discussions with project partners a new test method for SOFC lifetime prediction is presented. Originally, it was also the intention to include experience from specific lifetime testing of SOFC systems at Risø – DTU laboratories, but as these activities has taken place at a much later time than originally expected (Further explained in 2.5), it has not been possible to incorporate these findings in the new proposal. The test method is written/formulated as an addition to the draft standard IES 62282-7-2 Ed. 1: Fuel cell technologies – Part 7.2: Single cell/stack performance test methods for solid oxide fuel cells (SOFC).

The approach is to test a cell stack in 2 types of tests, steady state and load/thermal cycling. The cycling test can be described as compressed rather than accelerated since the degradation process is not enhanced by for example increased stack temperature and increased load. The system integrator defines a performance limit depending on the market demands etc. and can define lifetimes for cycling operation and steady state operation.

The principle is illustrated in Figure 2 below.

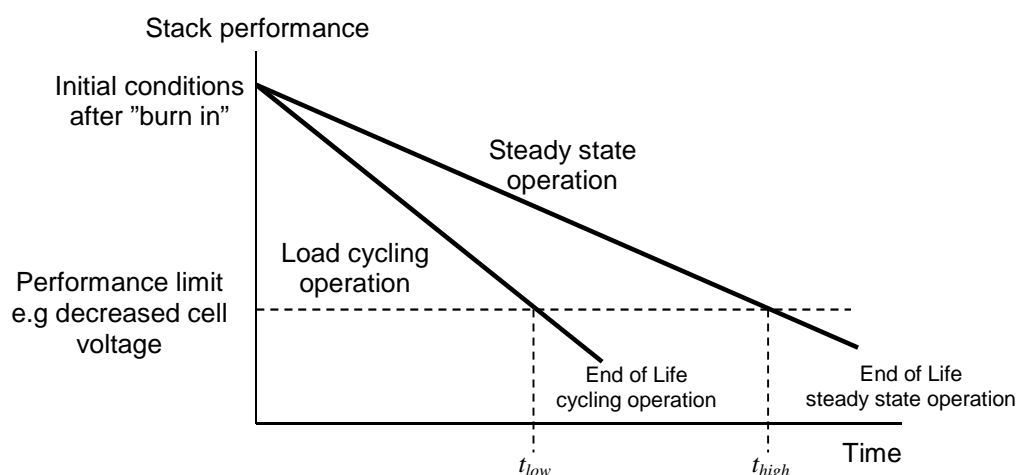


Figure 2 Principle of suggested lifetime prediction based on cycling and steady state durability tests

A model has to be used to predict the lifetime between t_{low} and t_{high} . This model is not yet derived. It shall use a representation of the operating pattern as input parameter. The difference between degradation rate for the steady-state and cycling operation can be interpreted as a measure of the stack robustness. Further details can be found in appendix D.

2.5 Presentation and discussion with potential stakeholders

The idea about international harmonization of test procedures for accelerated lifetime testing of SOFC systems and the new proposal was presented at the 2nd Int. workshop on Degradation Issues of Fuel Cells in Thessaloniki, Greece, september 2011.

The purpose was to present the work and initiate a discussion and work on the topic. The seminar presentation contains the topics of harmonized testing, comparing data, test sequence, reporting of results and the end-of-life definition. It also points out that the system integrator predicts the lifetime based on stack tests and the appliance operation.

The audience consisted of a large part of the SOFC industry and SOFC research community. The discussion that followed the presentation showed a broad agreement on the necessity and importance of accelerated tests and harmonised test procedures. In many of the presentations at the workshop it was clear that some kind of accelerated testing of durability and lifetime were used. Our work to develop a test procedure and lifetime prediction was

well received and the importance was stressed. However, there was not sufficient commitment at the time of the conference to engage and participate in an international workgroup for preparing and maturing a common standard for accelerated lifetime testing of SOFC fuel-cell systems.

The presentation can be found in appendix E.

2.6 Project milestones related to lifetime tests

With reference to the original project description, the milestones are achieved according to the table below. A few comments to the milestones are added after the table.

Milestone	Report/Appendix
2.1-II Accelerated test procedure proposed	D, E
2.2-I Report of Standardisation pre-survey	A
2.2-II Meeting of interest group for standard development	E
2.2-III Formulation discussion basis	E
2.2 IV Formulation of 1 st draft version of standard	–

The following comment from a previous report of the project progress¹ concerns milestone 2.2 III “Originally, an accelerated test procedure should have been defined by this time. However, it has not yet been possible to start the actual testing, as the test rig was not operational due to required substantial installation efforts. Therefore, the current procedure is a proposal until it has been tested and verified.”

Milestone 2.2 IV “Formulation of 1st draft version of standard” was deleted because it became clear in September 2011 that it was not possible to create an international working group with the objective to formulate a standardized accelerated lifetime test of SOFC stacks.

¹ Anke Hagen/Eva Ravn Nielsen, Risø DTU, “Test and Approval Center for Fuel Cell and Hydrogen Technologies: Phase 1. Initiation”, 2012

Appendix A

Accelerated lifetime test of SOFC stacks. Prestudy

July 2012

Accelerated lifetime test of SOFC stacks

Prestudy

Customer Report
July 2012

Accelerated lifetime test of SOFC stacks

Prestudy

Mikael Näslund

Title : Accelerated lifetime test of SOFC stacks

Report
Category : Customer Report

Author : Mikael Näslund

Date of issue : 03-07-2012

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Summary

The stack temperature and cycling are often mentioned as the main factors affecting the degradation. Degradation is normally shown as degradation as function of time for a constant load or the number of load or thermal cycles. No direct definition or description of accelerated test has been found.

A few papers discuss directly or indirectly the issue of accelerated tests.

A few models suggest that the Arrhenius equation, Blacks equation and Weibull distribution are included in a model for a lifetime prediction. These models seem not to be validated using real SOFC stack data.

A number of issues directly associated with accelerated lifetime tests and/or calculation are still not answered. A questionnaire to relevant persons shall include:

- Definition of system boundaries
- Definition of stack end-of-life
- etc

Relevant persons for the questionnaire are identified in the survey of SOFC stack developers and system integrators.

1 Introduction

The expected lifetime of 40,000 hours for SOFC stacks in the future imposes difficulties in the development work. It is urgent that an accelerated test procedure is discussed and developed for an efficient and harmonised method to predict the lifetime.

This report will be the first step in the work of initiating a work toward a harmonised test method to predict the SOFC lifetime.

Information is gathered from primarily a web search.

Information on cycling tests and experiences have been noted since cycling may be a part of accelerated lifetime tests and treated in future reports.

It is also the intention to formulate question for a questionnaire. This can be sent to key persons in order to gather aspects on a lifetime method.

2 SOFC stack manufacturers

In this chapters SOFC stack manufacturers and developers are collected. They are selected as parties considered interested in the development of a test procedure for accelerated lifetime tests of SOFC stacks.

The SOFC stack manufacturers are divided into three segments, manufacturers/developers of stacks for residential use, larger units and mobile units. This is of course only a rough segmentation.

2.1 Residential SOFC

Topsøe Fuel Cells

“Topsøe Fuel Cell focuses on solid oxide fuel cell technology - SOFC - which is the most efficient fuel cell technology available.”

“The Topsøe PowerCore™ integrates all SOFC-specific hot components, making system integration more simple for the appliance integrator. The commercial appliance is marketed by the system integrator...The Topsøe PowerCore™ for micro CHP applications is designed for systems with an output of 1 kW. This means that the Topsøe PowerCore™ can supply the major part of the electricity for a typical household.”

Web site: <http://www.topsoefuelcell.com/>
Address: Topsøe Fuel Cell, Nymoellevej 66, DK-2800 Kgs. Lyngby
Contact: Mette Juhl Jørgensen Chief Operations Officer, Operations,
Nymøllevej 66, DK-2800 Kgs. Lyngby, Phone: +45 4527 2024
(direct), Mobile: +45 2265 7568

Accelerated test work: –

Ceramic Fuel Cells

“CFCL will be the supplier of choice for reliable and high electrically efficient solid oxide fuel cell products, which manufacturers can easily integrate into micro generation appliances for the European market.”

Web site: <http://www.cfcl.com.au/>

Address: Ceramic Fuel Cells Limited, 170 Browns Road, Noble Park,
Victoria 3174, Australia
Contact: Karl Föger (Chief Technology Officer)

Accelerated test work: Result of degradation for a single cell, >23,000 hours, and cell stack shown in /1/. Nothing mentioned about accelerated tests.

Ceres Power

“The fuel cell stack is a layered construction of metal supported fuel cells separated by stainless steel interconnects which enable fuel and air to flow to either side of each fuel cell. The unique construction of welded sub-assemblies and gasket seals provides integrity and durability.”

Intermediate temperature SOFC for residential CHP systems. 800W AC output, Electric efficiency >34% (LHV).

Web site: <http://www.cerespower.com/>
Address: Viking House, Foundry Lane, Horsham, West Sussex
RH13 5PX, UK
Contact: Phil Whalen (Technology Director ,”Phil joined Ceres Power in July 2009 as Technology Director and is responsible for technology development and advanced engineering.” Ceres web site)

Accelerated test work: From /2/: “Rapid load-following & thermal cycling without degradation”, “ Welded cells aggressively thermally cycled between 100°C and 600°C – cycle time < 5 mins”, “No measureable degradation in cell performance after 100 cycles (equivalent to years of operating lifetime for a typical UK house based on real-life energy demand data).”

Hexis AG

“Hexis Ltd. belongs to the worldwide leading companies in the field of the high-temperature fuel cell technology (SOFC - Solid Oxide Fuel Cell) for stationary applications in the small power range.”

Hexis Galileo 1000 in field test. 1 kW electric output and 2 kW thermal output.

Web site: <http://www.hexis.com>

Address: Hexis Ltd., Zum Park 5, P.O. box 3068,
CH-8404 Winterthur

Contact: Volker Nerlich, Dr. Andreas Mai, andreas.mai@hexis.com

Accelerated test work: No such studies mentioned. Stack lifetime of 24,000 hours in the laboratory and >9,000 hours in the field /3/.

Delphi

“Delphi is focusing on the development of solid oxide fuel cells (SOFC) that generate electric power for commercial vehicles, stationary power generation, and military applications.”

Develops SOFC cells and stacks for system integration by United Technologies (UTC).

Web site: <http://delphi.com/manufacturers/auto/fuelcells/>

Address: Delphi, P.O. Box 20366, M/C 146 Hen 575, Rochester, New York 14602-0366, U.S.A.

Contact: Steven R. Shaffer, Chief Engineering - Fuel Cell Development,
Phone: [1] 585.359.6615

Subhasish Mukerjee, SOFC Stack Technology Leader, Propulsion and Fuel Cell Center, subhasish.mukerjee@delphi.com

Steven R. Shaffer, Chief Engineer Fuel Cell Development,
steven.shaffer@delphi.com

Accelerated test work: Only standard degradation curves, constant power and thermal cycling (10 h cycle). “Fuel Cell Seminar 2009” presentation.

Staxera

“Staxera GmbH is manufacturer and supplier of solid oxide fuel cell (SOFC) integrated stack modules (ISMs). Staxera supplies [ISMs](#), not complete SOFC systems.

To satisfy the market demand for SOFC systems, staxera and EBZ have begun a joint SOFC system development program, focusing on high electrical efficiency and based on steam reforming of natural gas.”

Staxera delivers 1 kW stacks to Vaillant in the German Callux demonstration program.

Web site: <http://www.staxera.de/SOFC-systems.768.0.html?&L=1>

Address: staxera gmbh, Gasanstaltstrasse 2, 01237 Dresden, Germany

Contact: Björn Erik Mai, Christian Wunderlich,
christian.wunderlich@staxera.de

Accelerated test work: “The SPIN test concept with its realistic thermal boundary conditions allows the introduction of new test methods such as accelerated thermal cycling.”¹

SPIN = Systemnahe Prüfstandsintegration, hotbox simulation with stack temperature controlled by anode and cathode gases. Thermal cycling showed in graphs with an approximate cycle time of 10 hours. Accelerated thermal cycling tests mentioned (see above) as a possible future option but not described.

Prototech

“Prototech designed and built a 3 kW SOFC pilot plant in cooperation with BKK and Innovation Norway. The plant was set in operation on 13 March 2008”.

Web site: <http://www.prototech.no>

Address: Visiting Address, CMR Prototech, Fantoftvegen 38, Bergen, Norway, Postal address, Prototech AS, P.O. Box 6034 Postterminalen, NO-5892 Bergen, Norway

Contact: Helge Weydahl(?)

Accelerated test work: No accelerated tests mentioned in June 2009 /4/.

¹ http://www.fuelcellmarkets.com/staxera/news_and_information/3,1,15168,1,27510.html

HTc - HTCeramix

“HTceramix SA is a dynamic and rapidly progressing developer of high temperature electroceramic applications in the field of energy and gas conversion devices. At the heart of its development is the SOFCConnex™ based Solid Oxide Fuel Cell stack...” owned by SOFCPower in Italy. HotBox demonstrated in Dantherm system.

Web site: <http://www.htceramix.ch>
www.sofcpower.com

Address: HTceramix, 26 Avenue des Sports, CH-1400 Yverdon-les-Bains, Switzerland

Contact: info@htceramix.ch

Accelerated test work: last news on HTceramix web site 2010: “65% electric efficiency achieved on SOFCpower’s SOFC stack”.

KERAFOL

“Kerafol – Keramische Folien GmbH develops and produces ceramic tapes for a wide range of applications using a special manufacturing process... Kerafol has played an active role in the field of solid oxide fuel cells, specifically scandium-doped fuel cells, since development of the technology began in the 1990’s”

Web site: <http://www.kerafol.com/en/home.html>

Address: Kerafol Keramische Folien GmbH, 92676 Eschenbach/Germany

Contact: Isabell Koppe, Marketing Director,
isabell-koppe@kerafol.com

Accelerated test work: No degradation information found so far.

AVL

Stack testing in the METSOFC project, APU?

Web site: <https://www.avl.com/fuel-cell-engineering>

Address: AVL List GmbH, Hans-List-Platz 1, A-8020 Graz, Austria

Contact: Dr. Martin Schüssler, Project Manager Fuel Cell Systems,
martin.schuessler@avl.com

Accelerated test work: No degradation information found so far.

Bloom Energy

100 kW, >50% efficiency, SOFC unit launched in early 2010.

Web site: <http://bloomenergy.com>

Address: Bloom Energy, 1252 Orleans Drive, Sunnyvale, California
94089

Contact: Venkat Venkataraman, Ph.D Vice President Product
Development

Accelerated test work: No test result or similar found.

Acumentrics

“We are able to produce from 250 watts to 2 kilowatts of AC or DC electrical power output in robust and discrete packages.”

Web site: <http://www.acumentrics.com>

Address: **Acumentrics Corporation**, 20 Southwest Park, Westwood,
MA 02090-1548

Contact: sales@acumentrics.com, Neil Fernandes, Senior Fuel Cell Processing Engineer, nfernandes@acumentrics.com

Accelerated test work: No degradation information found so far.

St Andrews Fuel Cells

“St Andrews Fuel Cells Limited was spun out from the University of St Andrews in 2005 having been created to exploit an innovative new solid oxide fuel cell design, called ‘SOFCRoll’. The business is focused on making SOFCRoll a commercially viable technology for low kilowatt, transportable fuel cell applications, combined heat and power systems and other stationary power systems.” Last news on web site: September 2008.

Web site: <http://www.standrewsfuelcells.com/>
Address: St Andrews Fuel Cells Limited, New Technology Centre,
North Haugh, St Andrews, Fife KY16 9SR, United Kingdom
Comment: Web site not available/found November 2010, Company still
existing?

NexTech

“NexTech Materials is developing solid oxide fuel cell and stack technology based on a new planar cell design, called the *FlexCell*TM. This cell design offers a number of important advantages relative to contemporary cell and stack designs, primary among them being the ability to design SOFC power systems with high gravimetric and volumetric power density, high electrical efficiency, and the ability to use sulfur-containing fuels.

Fuel cell stacks based on Cathode Supported Electrolyte Tubes consist of bundles of interconnected tubes which are typically sealed into a common air plenum, with oxidant being delivered down the axis of the tube to a closed end. Depleted air is collected at the open end of the tube. NexTech's cathode supported electrolyte tubes are produced using in-house extrusion and co-firing technology.”

Web site: <http://www.nextechmaterials.com/> ,
<http://www.fuelcellmaterials.com/>
Address: 404 Enterprise Drive, Lewis Center, Ohio 43035, USA
Contact: Scott Swartz s.swartz@nextechmaterials.com (planar SOFC)
Matthew Seabaugh,
m.seabaugh@nextechmaterials.com (tubular SOFC)
Rick Lesueur, rhl@nextechmaterials.com (tubular SOFC)

Accelerated test work: Standard degradation data, i.e. steady state and cycling degradation.

2.2 Power plant SOFC

The US SECA initiative/program (Solid State Energy Conversion Alliance)

“The Solid State Energy Conversion Alliance (SECA) was initiated in the fall of 1999 bringing together government, industry, and the scientific community to promote the development of environmentally friendly solid oxide fuel cells (SOFC) for a variety of energy needs. SECA is an alliance of industry groups who individually plan to commercialize SOFC systems for pre-defined markets; research and development institutions involved in solid-state development activities; and government organizations that provide funding and management for the program. The SECA alliance was formed to accelerate the commercial readiness of SOFCs in the 3 kW to 10 kW for use in stationary, transportation, and military applications.

“Reduce SOFC-based electrical power generation system cost to $\leq \$400/\text{kWe}$ (2002 dollars) for a $>100\text{MW}$ Integrated Gasification Fuel Cell (IGFC) power plant, exclusive of coal gasification and CO_2 separation subsystem costs. Achieve an overall IGFC power plant efficiency of $\geq 50\%$, from coal (HHV) to AC power (inclusive of coal gasification and carbon separation processes). Increase SOFC stack reliability to achieve a design life of $>40,000$ hours”.

In the SECA program participates Rolls Royce, Siemens, UTC

Web site: <http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca>

Address: –

Contact: David Brengel, Project Manager

Rolls Royce

“Rolls-Royce Fuel Cell Systems Limited (RRFCS) is developing solid-oxide fuel cell (SOFC) systems for megawatt scale, stationary power generation applications”/5/.

Web site: <http://www.rolls-royce.com>

Address: –

Contact: Richard Goettler (Manager Fuel Cell Development, 2009), Dr. Michael Jörger, Manager Fuel Cell Development, michael.jorger@rffc.com

Accelerated test work: No degradation information found so far.

Siemens

Develops flat SOFC for coal syngas in MW size.

Web site: <http://www.energy.siemens.com/hq/en/power-generation/fuel-cells/>

Address: Freyeslebenstr. 1, 91058 Erlangen, Germany

Contact: Mr Joachim Große (FuelCellToday)
Dr. Joachim Hoffmann, Technical Program Manager Stationary Fuel Cells (SOFC), hoffmannjoachim@siemens.com,
Frankenstr. 70-80, D-90461 Nuremberg, Germany

Accelerated test work: SECA 2010 presentation /6/ only contains standard degradation information.

Versa Power

“Versa Power Systems’ focus is on advanced SOFC cells, stacks and power plants for stationary and mobile applications. The company is currently developing pre-commercial, 2 kW to 10 kW prototype systems for field trial demonstrations.”

Versa Power develops SOFC technology used by Fuel Cell Energy (system integrator) in larger multi MW systems).

Web site: <http://www.versa-power.com>

Address: Versa Power Systems, 8392 Continental Divide Road, Suite 101, Littleton, CO 80127-4250 USA
Versa Power Systems, 4852, 52nd Street SE, Calgary, Alberta, Canada T2B 3R2

Contact: Brian Borglum brian.borglum@versa-power.com (?)

Accelerated test work: “Investigate degradation mechanisms at various operating conditions” (2009 Fuel Cell Seminar) /7/. Only standard degradation curves shown in presentation.

Fuel Cell Energy

System integrator of the Versa Power SOFC technology.

Fuel Cell Energy has MCFC products in the 300 – 3000 kW range.

Web site: <http://www.fuelcellenergy.com/>

Address: 3 Great Pasture Road, Danbury, CT 06813 (Global HQ)

Contact:

Accelerated test work: No degradation information found so far.

UTC – United Technologies

“UTRC's technology spans from atomistic modeling of catalyst through stack development to full-scale demonstration of integrated systems”

SECA Phase I minimum requirements: <2% power degradation/1000 hours.

Test sequence: Start-up, peak power test, Steady state test and shut-down

Test duration: 5,000 hours (1,500 hours in Phase I)

Web site:

<http://www.utrc.utc.com/pages/ResearchInnovation/SOFC.html>

Address: United Technologies Research center, 411 Silver Lane, East Hartford, CT 06108, USA

Contact:

Accelerated test work: SECA Phase I minimum requirements.

<2% power degradation/1000 hours. Test sequence: Start-up, peak power test, Steady state test and shut-down. Test duration: 5,000 hours (1,500 hours in Phase I). Durability: constant current durability test, thermal cycling, stack tested with real hydrocarbon fuel reformat (UTC/Delphi) /8/.

2.3 Research organisations

Jülich – Institute of Energy Research

“Research Centre Jülich works on the construction of SOFC stacks using the substrate cell technique.”

Web site: http://www.fz-juelich.de/ief/ief-3/fuel_cells/sofc/

Address: Forschungszentrum Jülich GmbH, Project Fuel Cell (PBZ),
Leo-Brandt-Str., D-52425 Jülich, Germany

Contact: r.steinberger@fz-juelich.de

Accelerated test work: –

ECN – Energy Research Centre of the Netherlands

“” Only PEM?

Web site: <http://www.ecn.nl/units/h2sf/rd/fuel-cell-rd-activities/>

Address: Mail: Energy research Centre of the Netherlands (ECN),
P.O. Box 1, 1755 ZG Petten, The Netherlands
Visit: Westerduinweg 3, 1755 LE Petten, The Netherlands

Contact: Frank de Bruijn

Accelerated test work: No degradation information found so far.

Ecole Polytechnique Federal de Lausanne - EPFL

Accelerated tests on SOFC and electron microscopic analysis

Web site: <http://cime.epfl.ch/page-26834.html>

Address: EPFL-SB-CIME-GE, MXC 134 (Bâtiment MXC), Station 12,
CH-1015 Lausanne, Switzerland

Contact: Aicha Hessler, aicha.hessler@epfl.ch
Jan van Herle, Industrial Energy Systems Laboratory (LENI),
jan.vanherle@epfl.ch

Accelerated test work: “Especially, lifetime requirements exceeding 40'000 h are not fulfilled by current systems. On this time-scale it becomes unreasonable to test devices and systems in the laboratory in order to ensure system longevity. Rather, methods have to be found to accelerate the degradation of the SOFC devices over time in order to be able to predict the durability from much shorter testing periods.

As no accelerated testing should be undertaken before understanding the underlying degradation phenomena, this project will turn more towards understanding.”

National Fuel Cell Research Center – University of California, Irvine

“The goal of the NFCRC is to facilitate and accelerate the development and deployment of fuel cell technology and fuel cell systems; promote strategic alliances to address the market challenges associated with the installation and integration of fuel cell systems; and to educate and develop resources for the various stakeholders in the fuel cell community.”

Web site: <http://www.nfcrc.uci.edu/2/default.aspx>

Address: University of California, Irvine
Irvine, California 92697-3550, USA

Contact: –

Accelerated test work: Beta Test Overview. “Multi-month testing of prototype units stands as a core practice at the NFCRC, and is key to the development of technologies and their application in marketplace.

The beta testing / demonstration component supports the multi-month and multi-year beta testing of prototype units. Beta testing is the heart of the program philosophy of the NFCRC. It serves three principal roles, all of which are fundamental to the principal operations of the NFCRC:

Beta testing provides critical feedback to the manufacturer prior to commercial launch. The testing determines performance, reliability, and the success of engineering. The process allows for the demonstration of reliability, availability, maintainability, durability, and usability (RAMDU) while concurrent system improvements are made in an objective, yet scrutinizing research setting.

Beta testing provides a showcase, at a neutral and objective site (the university), for potential users of fuel cell technology to critically assess the attributes and liabilities.

Beta testing provides insight and perspective into the limiting science that, if addressed, could significantly affect the evolution of fuel cell technology. Faculty and researchers identify beta testing projects through a bridging that promotes interaction between the university, the manufacturer, and the user.“

Fraunhofer Institute for Ceramic Technologies and Systems IKTS Micro and Energy Systems

“SOFC fuel cells are one core competence of our department. R&D areas include components, stacks, complete energy systems, and their ceramic reactors. We put focus especially on the use of biogenic energy carriers. Practical work is supported by an efficient simulation of materials, devices and systems based on experimentally determined material parameters.”

Web site: <http://www.ikts.fraunhofer.de/en/>

Address: Fraunhofer Institute for Ceramic Technologies and Systems
IKTS, Winterbergstr. 28, 01277 Dresden, Germany

Contact: Dr.-Ing. Mihails Kusnezoff, Phone +49 351 2553-7707,
Fax +49 351 2554-134, mihails.kusnezoff@ikts.fraunhofer.de

2.4 R&D programs

FCTESTNET and FCTESQA (2006-2010)

“The main objective of the FCTESTNET is to create a network of research and industrial organisations involved in development and testing of fuel cells (FC), FC systems and FC applications. This network will produce proposals for harmonisation of test procedures at the level of FC systems down to stacks and cells.”

“The main aim of FCTES^{QA} is to address the aspects of pre-normative research, benchmarking, and validation through round robin testing of harmonised, industry-wide test protocols and testing methodologies for fuel cells”

Web site: <http://ie.jrc.ec.europa.eu/fctestnet/>
<http://fctesqa.jrc.ec.europa.eu/>
Address: European Commission, Joint Research Centre-Institute for
Energy, Cleaner Energies Unit, P.O. Box 2, NL-1755 ZG Pet-
ten, The Netherlands
Contact: Georgios Tsotridis, georgios.tsotridis@jrc.nl

Real SOFC (2004-2008)

“The aim of the EU Integrated Project Real-SOFC is to solve the persisting problems of ageing with planar Solid Oxide Fuel Cells (SOFC) in a concerted action of the European fuel cell industry and research institutions.”

Web site: <http://www.real-sofc.org/>
Address: Forschungszentrum Jülich GmbH, Project Fuel Cell (PBZ),
Leo-Brandt-Str., D-52425 Jülich, Germany
Contact: –

SOFC 600 (2006-2010)

“SOFC600 is an Integrated Project funded by the European Commission in the Sixth Framework Programme. The full title of the project is 'Demonstration of SOFC stack technology for operation at 600°C’”

Web site: <http://www.sofc600.eu/>
Address: Energy research Centre of the Netherlands, Westerduinweg 3,
1755 ZG Petten, The Netherlands
Contact: Mr Bert Rietveld (g.rietveld@ecm.nl)

Flame SOFC (2005-2009)

“The overall objective of the Flame SOFC project is the development of an innovative SOFC-based micro-CHP system capable to operate with different fuels and fulfilling all technological and market requirements at a European level. The main focus concerning the multi-fuel flexibility lies on different natural gas qualities and LPG, but also on liquid fuels (diesel like heating oil, industrial gas oil IGO and renewables like FAME). The target nominal net electrical output is 2 kW_{el} (stack electrical output ca. 2,5 kW),

which is expected to represent the future mainstream high volume mass market for micro-CHPs.”

Web site: <http://www.flamesofc.org/public/>

Address: Energy research Centre of the Netherlands, Westerduinweg 3,
1755 ZG Petten, The Netherlands

Contact: Mr Bert Rietveld (g.rietveld@ecn.nl)

METSOFC

“The objective of the METSOFC project is to develop the next generation of metal-based SOFC stack technology”. It is a part of the EU 7th Framework program

Web site: <http://www.metsofc.eu/>

Address: –

Contact: Jens Olsen, Topsoe Fuel Cell jols@topsoe.dk

TEKES – Fuel Cell 2007-2013

“The programme vision is that Finnish industry will develop products and services based on fuel cell technology for global markets. This will take place in cooperation with foreign technology partners, the research community and the Finnish government.

The priority areas are stationary and portable fuel cell applications and specialist vehicles with fuel cell power modules.”

Web site:

http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/Poltto_kennot/en/etusivu.html

Address: –

Contact: Programme Manager: Heikki Kotila heikki.kotila@tekes.fi

Project Coordinator: Anneli Ojapalo

anneli.ojapalo@spinverse.com

Callux

“The German Ministry for Transport, Construction and Urban Development (BMVBS), launched together with nine partners from industry Germany’s

biggest practical test for fuel cell heating systems for domestic use under the project name Callux.

Three system manufacturers are involved in the project - BAXI INNOTECH, Hexis and Vaillant - as well as five utility companies - EnBW, E.ON Ruhrgas, EWE, MVV Energie, VNG Verbundnetz Gas.”

Web site: <http://www.callux.net>

Address: –

Contact: Contact sheet on the web site

2.5 Test rig suppliers

FuelCon

Fuelcon develops and sells test rigs and software for fuel cell testing.

Web site: <http://www.fuelcon.com>

Address: FuelCon AG, Steinfeldstr. 1, D-39179 Magdeburg-Barleben, Germany

Contact: –

EBZ

“EBZ has nearly one decade of experience in testing of Solid Oxide Fuel Cells (SOFC). Stacks from different developers have been installed and successfully tested: Fraunhofer IKTS, Staxera, FZ Jülich and HTceramix. Furthermore, EBZ was partner for stack testing in the European research project REAL-SOFC. Based on these experiences, EBZ offers its knowledge in standard testing procedures and benchmark conditions as engineering service.”

Web site: <http://www.ebz-dresden.de/>

Address: EBZ Entwicklungs- und Vertriebsgesellschaft Brennstoffzelle mbH, EBZ GmbH EBZ GmbH Marschnerstraße 26 Seifhennersdorfer Str. 16, 01307 Dresden, Germany

Contact: –

Accelerated test work: EBZ mentions degradation and cycling tests in the company presentation.

3 Review of accelerated stack tests

The compilation of SOFC manufacturers and other relevant partners shows that accelerated testing of SOFC components and systems, and lifetime estimation, is not a standard procedure that is made public.

3.1 Short review of selected papers

A literature search among the academic journals and conference contributions does not give more information. However, only very few papers can be mentioned and the discussion regarding lifetime of fuel cells.

The author in /9/ states that “stack test results are too complicated to analyse”...”a disaggregated model of single degradation mechanisms could be suitable for evaluation of the single effects”...”a complete model could then be achieved by reaggregating results”

A clear focus on SOFC and steady-state operation is put in /10/. “Accelerating testing provides a tool where the cell degradation rate is increased in order to fail or degrade the cell much faster. In doing so, one may fit the resulting data to some empirical or semi-empirical equation.”

The authors propose the following function to calculate the cell voltage V_{cell} as a function of time t

$$V_{cell} = A_1 + A_2 \exp\left(-\frac{t}{\alpha_1}\right) + A_3 \exp\left(-\frac{1}{\alpha_2}\right)$$

where A_1 , A_2 , A_3 , α_1 and α_2 are constants. They further suggest that if temperature is the only accelerating parameter the Arrhenius Lifetime Relationship may be used. The time to failure τ (hours) is calculated as

$$\tau = A \exp\left(\frac{E}{kT}\right)$$

where A is a constant (hours), E is the activation energy, k is Boltzmanns constant and T is the temperature. They also suggest that Black’s equation may be used to calculate the time to failure τ in a modified version as

$$\tau = \frac{A}{J^n} \exp\left(\frac{E}{kT}\right)$$

where A and n are constants, J is the current, E is activation energy and T is the temperature. A , n and E are determined from experiments. Black's equation is usually used in accelerated testing of semiconductors.

A general discussion on fuel cell based micro cogeneration degradation and the economic and environmental consequences of changed performance is made in /11/. The authors state that the performance degradation is a linear function of power density and/or proportional to the rate of thermal cycling.

Degradation rates are included in an overall economic evaluation. The rates are calculated from a number of investigations. "Cumulative degradation can therefore be expressed as a percentage performance loss per MW_eh output, and per 1000 thermal cycles."

4 Questionnaire

A questionnaire should contain the following topics/questions. It shall be the base for a discussion on the possible test procedure design and possible calculations. The questionnaire shall be design to allow elaborate answers to include all possible aspects of a test procedure. It means more work in evaluating the questions but the limited number of answers makes it reasonable and realistic.

- *System boundaries, cell, stack, including BoP, reformer etc*
Single cell
- *What is gained or loosed by different system boundary definitions?*
- *Definition of end-of-life*
- *Shall accelerated test be done until appliance end-of-life, or combined with a model to estimate the lifetime?*
cost of stacks and tests
- *Which degradation mechanisms are dominating and can be selected for testing?*
- *Possible to include the entire SOFC temperature range today and in the future in one test procedure considering all degradation mechanisms?*
- *Statistical methods and samples*
- *Fuels*
methane, hydrogen, reformat or coal syngas
- *Operation pattern considered for the lifetime estimation*
Will it be two different kinds of SOFC operation, constant load operation and dynamic modulating operation with or without thermal cycling?

- *Acceleration, how?*
Increased cell load, load/thermal cycling, increased temperature
- *Operation strategy planned or foreseen for the own products*
Shall supposed steady-state or dynamic operation influence the chosen test procedure?
- *How is the lifetime affected by variations in production tolerances*
Statistics, number of test samples?
- *How to guarantee that acceleration do not introduces a degradation mechanism that not will be present in real-life operation.*

References

- /1/ *Ultra-High-Efficiency Residential Power System*, Karl Föger and Trent Rowe, 3rd European Fuel Cell Technology Applications Conference, Rome, December 2009
- /2/ *Alternative energy products for global markets. CHP demonstration, site visit and preliminary results for the year ended 30 June 2010*, Ceres Power presentation 29th September 2010
- /3/ *Cogeneration in single family homes with fuel cell heating appliances*, V. Nerlich et al, 18th World Hydrogen Energy Conference 2010 - WHEC 2010
- /4/ *SOFC stack testing at Prototech – measurements for stable stack operation*, Helge Weydahl et al, Int. Symp. On Diagnostic Tools for Fuel Cell Technologies, Trondheim Norway, June 2009
- /5/ *Update on the Rolls-Royce Coal-Based SECA Program*, Richard Goettler and Ted Ohrn, 11th Annual SECA Workshop, July 2010
- /6/ *The Siemens Energy Coal Based SECA Program*, Joseph Pierre, 11th Annual SECA Workshop, July 2010
- /7/ *Development of Solid Oxide Fuel Cells at Versa Power Systems*, Brian Borglum, Fuel Cell Seminar, November 2010
- /8/ *SOFC Program Review*, David Brengel, 11th Annual SECA Workshop, July 2010
- /9/ *Degradation and Accelerated Testing Issues in SOFC*, Robert Steinberger-Wilckens, International Workshop on Accelerated Testing in Fuel Cells, October 2008, Ulm, Germany
- /10/ *Semi-Empirical Equations to Estimate SOFC Lifetime*, Gianfranco DiGiuseppe and Li Sun, 216th ECS Meeting, 4-9 October 2009, Vienna Austria

-
- /11/ *Fuel cell micro-CHP techno-economics: Part 2 – Model application to consider the economic and environmental impact of stack degradation*, A.D. Hawkes, D.J.L. Brett, N.P. Brandon, *Int. J. of Hydrogen Energy*, (34)2009, 9558–9569

Appendix B

Accelerated SOFC lifetime test procedures

July 2012

Accelerated SOFC lifetime test procedures

Project report
July 2012

Accelerated SOFC lifetime test procedures

Mikael Näslund

Dansk Gasteknisk Center a/s
Hørsholm 2012

Titel : Accelerated SOFC lifetime test procedures

Rapport kategori : Project report

Forfatter : Mikael Näslund

Dato for udgivelse : 04.07.12

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Summary

In this report some topics for accelerated tests of Solid Oxide Fuel Cells (SOFC) are identified for further discussions.

SOFC technology is approaching a commercial level. One of the most important performance parameters is durability or lifetime. To enable system integrators to compare stack lifetime of different manufacturers, standardization of testing and measuring principles are of vital importance.

As stack lifetime is approaching lifetimes of more than 50000 hours accelerated lifetime testing would be very beneficial for the continuous development work of SOFC stacks.

Therefore it is suggested that a new standard for accelerated testing and measuring of lifetime of SOFC stacks is developed. This may be a standard on its own or part of another standard. It is suggested that it could be included in the new IEC standard IEC 62282-7-2 ed.1: Single cell/stack- performance test methods for solid oxide fuels cells (SOFC).

The intention of this report is to act as an inspiration and common background for further discussions of the possibilities of a common standard for accelerated testing of SOFC stack lifetime.

SOFC systems will be used in various applications with different load profiles. It is suggested that the test standard includes a limited number load profiles that covers most of the typical applications.

The report includes a short review of existing papers upon the subject and suggestions for how to move on.

1 Introduction

The aim of the current study is to initiate a work to establish a widely accepted method to predict the lifetime of Solid Oxide Fuel Cells (SOFC). The method shall include accelerated tests and maybe a method to calculate the lifetime from the test results. It is a step beyond pure degradation studies.

There are two general approaches and goals for accelerated tests

- Accelerated tests in order to identify problems and *increase the lifetime*
- Accelerated tests to *predict the lifetime* of a certain cell or system generation

These tests will probably also include a number of test samples and a statistical analysis.

The following topics are discussed in this document:

- Lifetime definition.
- Load pattern for different applications and unit sizes.
- A review of recent lifetime test studies
- Proposal of a number of basic test designs

The document shall be used as background for further discussions, and some questions are left unanswered for this discussion.

1.1 Lifetime definition and test duration

The purpose of this study is to suggest a method to predict the *technical* lifetime of SOFC stacks or systems. What measure shall be used to predict the lifetime? 10% voltage drop has been mentioned.

What is a reasonable duration for an accelerated test? If we assume an acceleration factor of 10 it means a 4000 hour accelerated test to simulate 40.000 operating time. Shall the test alone be used for a lifetime prediction or should the test result be used in a lifetime calculation? A calculation reduces the necessary testing time or the acceleration factor.

A major issue is the level where the tests are done, acceleration tests of the cathode, cell or system? The degradation in SOFC is mainly caused by

- IR – increased internal resistance
- Cathode polarization

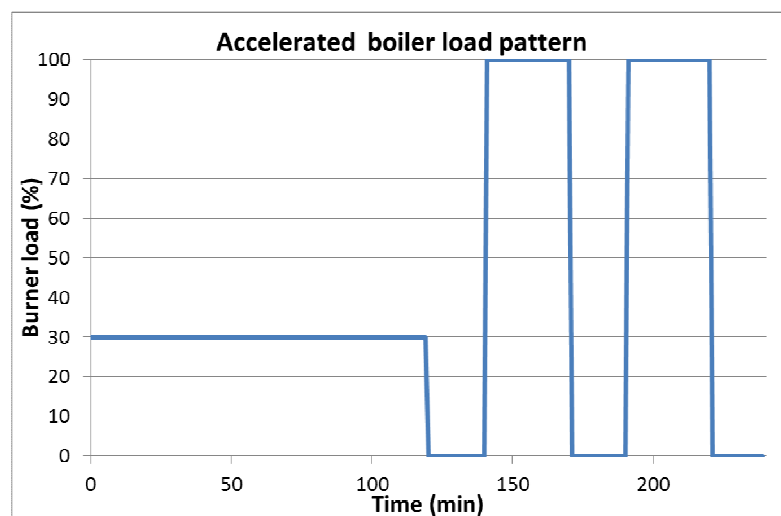
What are the origins of these losses? In the literature the major sources are a steady-state baseline degradation, thermal and load cycling.

Which are the proper ways to accelerate these mechanisms? Increased temperature, increased current density and cycling are suggested.

How is the acceleration factor determined or calculated?

1.2 A comparison – accelerated tests of gas boilers

Domestic gas boilers are tested by the manufacturers, not directly to predict the lifetime, rather to identify possible problems in the burner or the heat exchanger due to overheating. The acceleration may be realized by compressing the operational load pattern in order to get an acceleration factor of 4–6. The load pattern used in current accelerated test at DGC is shown as an example. The load pattern for one day is simplified to the loads that may cause problems, burner minimum and maximum input, and compressed from 24 hours to 4 hours. The acceleration factor is 6, and during 6 months will 3 years of operation be simulated, which is considered enough to force any problems to show.



Acceleration load pattern in tests of domestic gas boilers

The example shows the importance of defining the application for the accelerated lifetime test. The degradation mechanisms in fuel cells are not the same as in domestic gas boilers, but it is important to study an accelerated test of an appliance for partly the same application.

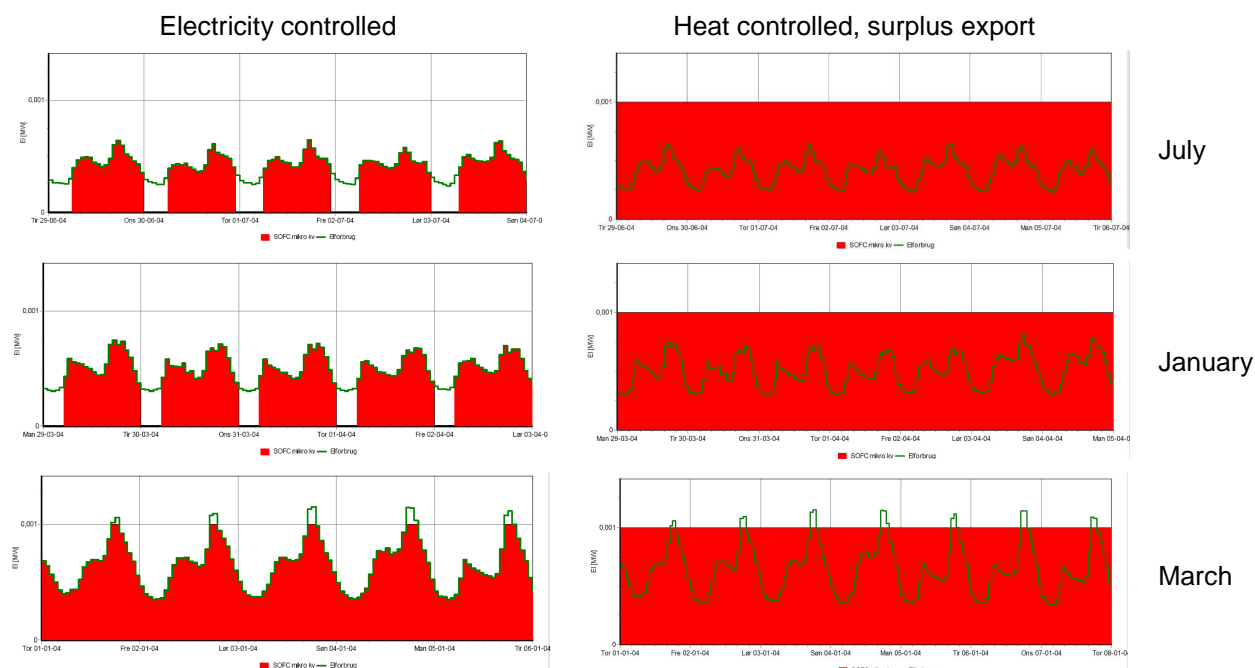
1.3 Load profiles and patterns for SOFC systems

The load pattern for a SOFC system may be split into two major installation types. This is an important issue when the test procedure is determined. In this section will different load patterns be discussed.

- The first type is characterized by a constant (maximum) load, or a load with small changes.
- The second type is characterized by a blend of on/off operation and a constant load operation between minimum and maximum load.

The first type may be decentralized power generation while the latter type may be a micro cogeneration unit in a single-family house. The load pattern is dependent on the regulatory framework regarding the possibility to export surplus electricity to the grid and a micro cogeneration size compared to the annual or seasonal heat demand.

The load profile for a micro cogeneration unit is also influenced by the regulatory and/or economical possibilities to export surplus electricity to the grid. The graphs below illustrate the difference. They show a DGC simulation of the SOFC (1 kWe) operation for a electricity demand controlled unit with no export of electricity (left) and a heat demand controlled unit with export of surplus electricity possible (right). The green curves show the electricity demand and the red area is the electricity production in the SOFC unit.

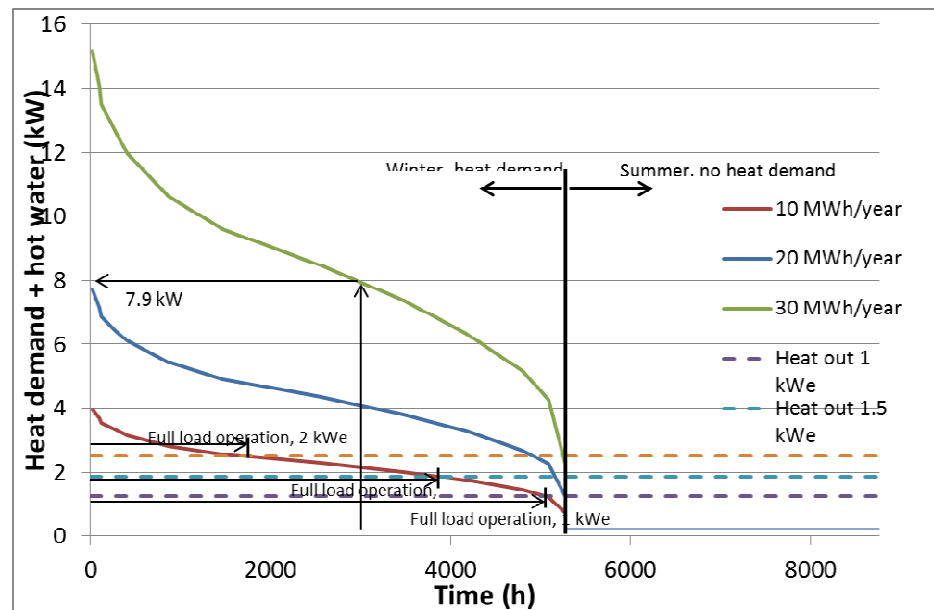


The heat controlled unit can also be described as a baseload application. This example shows two very different operating modes depending on the regulatory framework regarding surplus electricity to the grid.

The application is important for the load profile. Which profile should be selected, constant base load and/or a simulated micro cogeneration load profile?

The figure below shows some aspects of the fuel cell unit size and the annual heat demand. The climate data used for the annual efficiency of gas boilers in the Danish energy labeling system is used. The graph shall be read as the example marked in the graph. During 3000 hours is the heat demand equal to, or larger than 7.9 kW.

The three horizontal dotted lines show the thermal output from fuel cells with 40 % electric efficiency and 90 % overall efficiency. It is assumed that the fuel cell operation is heat controlled and all surplus electricity can be exported to the grid.



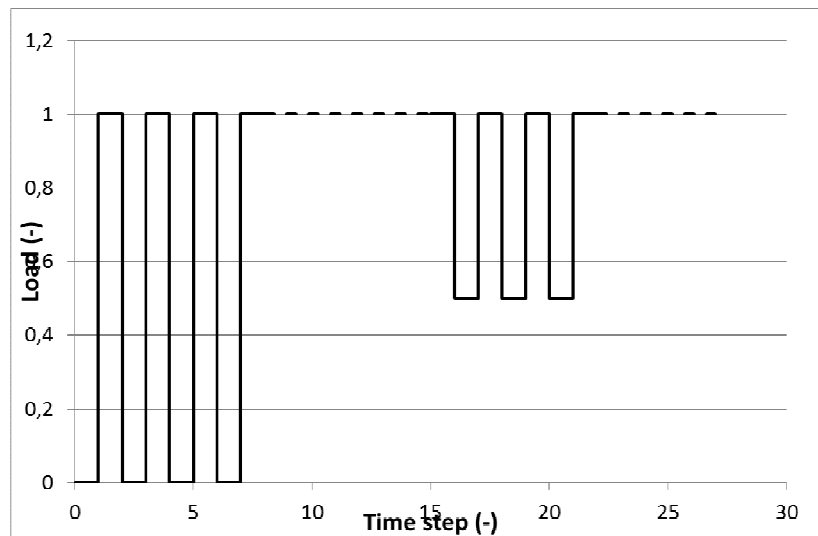
Heat demand and fuel cell micro cogeneration output

If we for example study the 10 MWh demand curve we observe that the 2.5 kW fuel cell unit will have approximately 1800 full load hours during the heating season while the 1.5 kW unit has 3900 full load hours and the 1 kW unit has 5100 full load hours, i.e almost the entire heating season.

An increased electric efficiency with unchanged overall efficiency reduces the thermal output and increases the number of full load hours during the heating season.

These examples have shown that both the sizing and the operation strategy influence the load pattern, and also different operating conditions which are assumed to influence the lifetime.

The load pattern is essential for the scope and definition of accelerated life-time tests. During the summer we can for example assume two daily load cycles in case the unit is in operation. The annual operation can then be simulated by a general pattern as described in the figure below.



Possible load pattern for SOFC tests simulating a micro cogeneration operation

Ideas and comments regarding the load profiles? Preferred/recommended?
Shall two lifetime predictions be defined, baseload and "micro cogeneration"?

1.4 Accelerated tests for other fuel cell technologies

1.4.1 Japanese PAFC lifetime prediction

A test standard for lifetime prediction of PAFC (Phosphoric Acid Fuel Cells) has been developed in Japan /2/. The tests include both single cell tests at accelerated conditions and test of cell stacks at reference conditions. All tests are made at steady-state conditions, i.e no load cycling or thermal cycling. Operation and load pattern of a PAFC: 100 % load??? Does this reflect the anticipated operation pattern of a PAFC unit?

2 Test procedures

A test procedure shall include a decision regarding the operational conditions, load pattern etc. Shall the test procedure reflect micro cogeneration or decentralized power generation?

Three basic test procedures are presented in this chapter for further discussion and evaluation. The model or method for using the test results is not further discussed in this document. However, it is necessary to keep in mind that the tests are designed to fit a model reflecting the real installations and operation.

It is also important that the acceleration load pattern and measurements do not affect the degradation mechanisms that will occur in the normal operation.

In the available presentations from conferences and seminars often use accelerated tests for other products are used as examples. It is essential that the operation of fuel cells in the real applications is studied if the life-time test procedure shall include stack or system.

2.1 Stack or system tests?

Shall the tests be made on the stack or the entire system. If the entire system is tested as a unit it will show the predicted lifetime for the end user. If the stack alone is tested will the system lifetime depend on the system integrator. This limitation can be avoided if the stack manufacturer prescribes a set of limits such as maximum operating temperature, load change gradients etc.

2.2 Degradation and acceleration factors/parameters

In [3] lifetime prediction is described in a presentation that summarizes the degradation topic at a workshop in 2007. The presentation is based on selected parts from three other presentations. These include the degradations mechanisms in the table below, a fuel cell specific presentation and a general presentation on accelerated testing. The view of the Australian manufacturer CFCL mentions the possibilities in material and component testing but

only states that stack testing is a significant challenge. Accelerated testing is described as “rapid cycling”.

Component degradation	Design/system degradation
Single cell degradation Sealing degradation Oxidation of interconnects Degradation of contact resistances Interaction between: <ul style="list-style-type: none"> - Glass/interconnect - Interconnect/cell - Contact layer/interconnect - Contact layer/cell 	Formation of hot spots Inhomogenous gas distribution/utilisation Unfavourable stack integration into the system Degradation due to unfavourable stack-preload (mechanical stress?)

The general presentation of accelerated testing is that higher acceleration factors is possible for “lower levels of integration”, i.e material or cells. A number of problems/pitfalls regarding accelerated testing are mentioned (probably from “Statistical Methods for Reliability Data” by Meeker and Escobar, 1998). These are:

- Multiple unrecognized failure modes
- Failure to quantify uncertainty
- Multiple time scales
- Masked failure modes
- Faulty comparison
- “Accelerating” variables can cause deceleration
- Untested design/production changes
- Drawing conclusions from specially-build units
- Reacting to a failure mode that would never occur in actual application

Steinbergers conclusion regarding lifetime prediction is:

- Stack test results are too complicated to analyse
- Full set of parameters to equip a ‘full’ stack model (including degradation) does not exist
- A disaggregated model of single degradation mechanisms could be suitable for evaluation of the single effects
- A complete model could then be achieved by reaggregating results

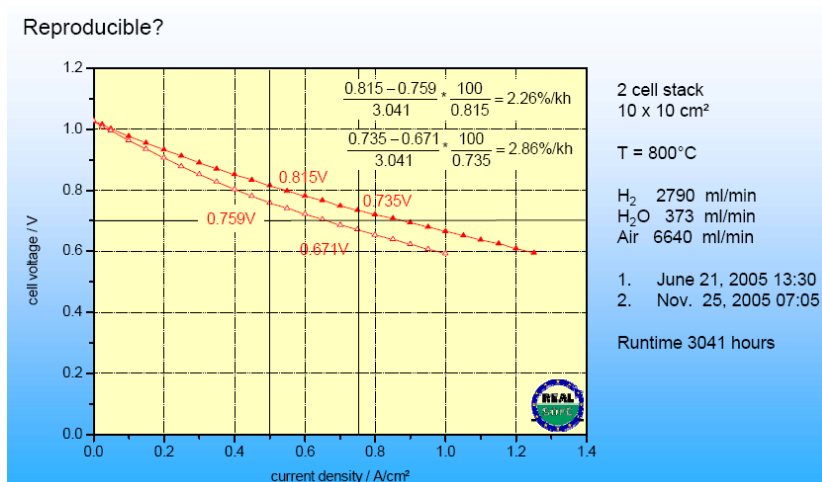
In a similar summary /4,5/ of degradation presentations at a workshop 2008 the following can be noted. Again, selected slides were used for the conclusions. The result is more specific and the following things are mentioned: common definitions, learning from other industries, tools in degradation analysis and approaches to degradation modeling. No results from systematic studies regarding determining acceleration factor were shown. If such correlations are not known such tests are critical for model development.

In /6/ are cycling effects and processes in SOFC cells from tests shown. The cycling frequency assumed in different applications are shortly discussed, and also the potential risk of accelerated tests.

The AVL /7/ Load Matrix seems to be a tool built on sample damage in the process to test and validate durability and reliability. The Load Matrix concept includes all steps from product concept to production. Detailed calculations regarding mechanics, wear etc. It combines different durability test, Failure oriented (worst case) and usage oriented (real use).

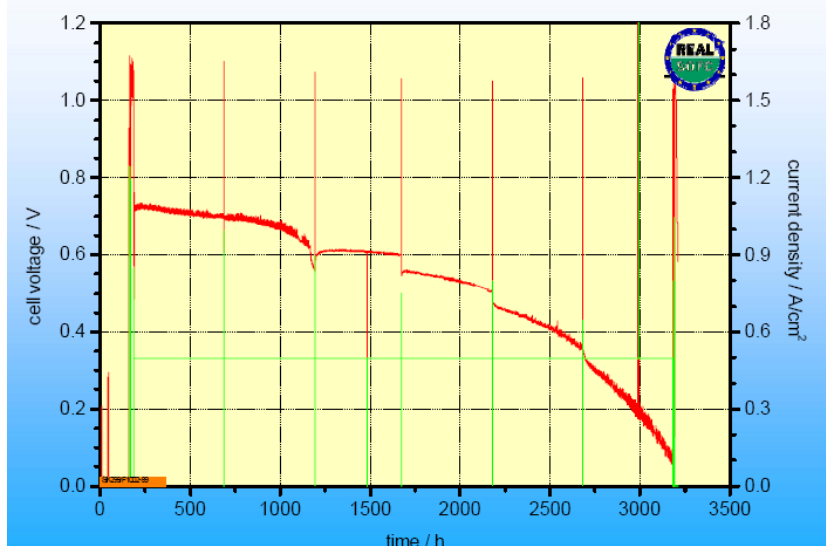
It is difficult to directly judge whether or not the Load Matrix is applicable for an accelerated lifetime test.

In /8/ several aspects of measuring and evaluating degradation are discussed. Two examples from his presentation are shown below. The upper graph shows a possible problem in choosing the current density for the calculation of the degradation rate. The calculated degradation rate is higher when a higher current density is chosen. The lower graph indicates that the test procedure itself may affect the lifetime. Determining the I/V curve at regular intervals seems to reduce the degradation rate and the calculated lifetime.



I/V curves for at stack at the start and after 3000 hours as illustration of possible problems in choosing the point for degradation calculation

Possible Influence of I/V measurements on degradation.



Is the regular I/V scan (peaks) affecting the degradation?

His conclusions are:

- Degradation should be expressed in absolute numbers
- Degradation should be expressed in an intrinsic property like the ASR (ASR = Area Specific Resistance?)
- Independent of the measurement conditions. This is perhaps possible when the mechanisms governing degradation are understood.

The table below shows that testing and lifetime prediction is not solved in detail for any system level. Advantages and disadvantages for any testing situation have to be further evaluated.

Level	Pros	Cons
-------	------	------

Cell	To be discussed	To be discussed
Short stack/stack	To be discussed	To be discussed
System	To be discussed	To be discussed

2.3 Operation and load patterns

In the previous chapter it was clearly shown that the anticipated load pattern for a fuel cell system was strongly dependent on the application and size of the unit. The test procedure shall clearly describe the kind of operation that is anticipated. It clearly affects the number of thermal and load cycles in the test procedure.

Common for all test procedures are the questions regarding the number of test samples, statistical analysis of the test results and the determination of the acceleration factor.

2.4 Compressed operation pattern

The basic idea of this test procedure is to simulate the expected operational pattern and keep the operation conditions such as temperature and stack current at normal design values. It is then similar to the earlier described accelerated test of gas boilers. The compression is obtained by reducing the steady-state operation time. Transients are created as in the real application, i.e. equal time (gradients) for load changes.

Compressed load pattern is not a relevant acceleration method for baseload operation.

Real operation simulated. Lacks steady-state degradation
--

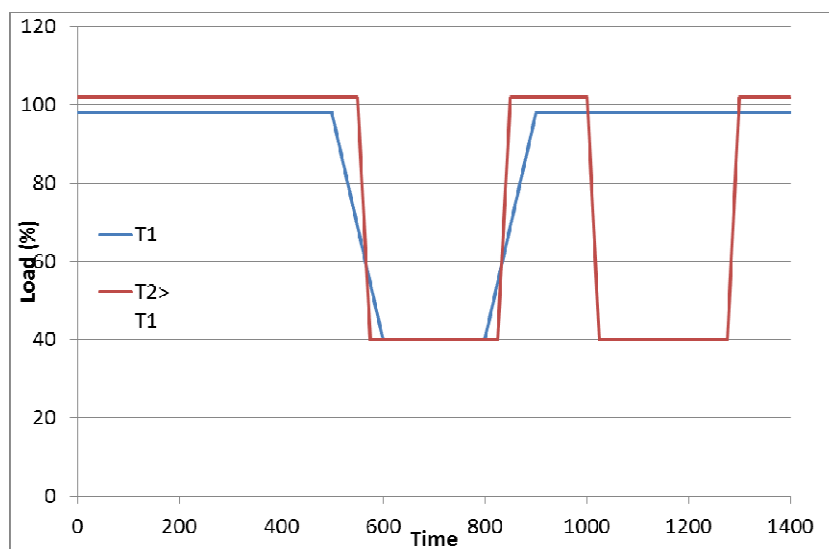
2.5 Off-design operation

A test in off-design conditions includes accelerated degradation due to increased stack temperature, current density and cycling gradients but the load pattern is equal to a real simulated installation.

Advantages and disadvantages as in the "Compressed operation pattern" but higher acceleration factor due to higher temperature etc.

2.6 Mix of compressed operation and off-design operation

The two test procedures described in previous section are partly mixed in this section. The principle is shown in the figure below. The blue line shows the operation in an installation. The red line shows an accelerated test where the stack temperature is increased, load changes are made faster and the load pattern is compressed.



Example of load changes in an accelerated test with different temperatures. The curves are separated for clarity.

3 Conclusions

The following list includes some of the questions and topics that have to be answered and discussed in the development of an accelerated test procedure.

- Definition of lifetime
- Preferred time for the lifetime tests and calculations
- Stack or system testing?
- The load pattern has to be determined
- How is acceleration achieved?
- Determination of acceleration factor

List of test results wanted for an evaluation of the potential of different models/methods

- Internal resistance as a function of time for two or more stack temperatures, and possible acceleration factor
- Temperature distribution as a function of time after at step increase in the load, time to achieve steady-state conditions after a load change.

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- /2/ *Accelerated life test methods for phosphoric acid fuel cell*, Japanese Industrial Standard JIS C 8802:2003
- /3/ Steinberger-Wilckens, R., *Lifetime Prediction. How can we approach the topic of 'accelerated testing'*, Int. Workshop on Degradation Issues in Fuel Cells, September 19-21 2007, Hersonissos, Greece
- /4/ Steinberger-Wilckens, R., *Summary of the HT sessions. The SOFC point of view*, Int. Workshop on Accelerated Testing in Fuel Cells, October 6-7 2008, Ulm, Germany
- /5/ Steinberger-Wilckens, R., *Degradation and Accelerated Testing Issues in SOFC*, Int. Workshop on Accelerated Testing in Fuel Cells, October 6-7 2008, Ulm, Germany
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Appendix C

Test methods for assessing durability of SOFC stacks

Topsoe Fuel Cell document

March 2011

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1 Scope

This document describes test methods for assessing durability of SOFC stacks. The methods are intended to be used for acquiring and treating durability data of SOFC stacks that can be exchanged between manufacturers and their customers. The methodology is also intended to be used by developers in order to acquire reliable data on stack durability.

2 Introduction

2.1.1 Designed operation condition, DOC

In order to have a good benchmark of degradation the SOFC stacks should in principle be run under the exact same conditions for proper comparison, i.e. same operating condition and the same rate of load cycling, temperature cycling etc. In reality this can not be done because manufacturers produce stacks designed for specific operating conditions i.e. for a specific system with specific specifications. For this reason this standard defines the test content and each manufacturer specifies a design operating point - a nominal operating point, referred to as DOC (designed operation condition) which is used as reference to determine degradation rate and as reference when setting conditions for durability tests.

DOC shall include current density, temperatures (furnace, air, and fuel inlet), fuel and air utilization, fuel composition and electrical efficiency. See section **5 Definitions** to see how these parameters are defined and section **4.1.1 Report DOC** for an example.

2.1.2 Degradation standards

The stack is tested at an operating condition (DOC) specified by the manufacturer continuously for 3000 hours and dynamically for 200 load cycles and exposed to 25 temperature cycles.

Degradation is to be reported as the change in power density, electric potential, and area specific resistance (ASR) over time. It is necessary to provide at least these three mutually dependent representations of degradation in order to give a comprehensive representation of stack durability. By reporting these three degradation representations, it will e.g. be transparent if a significantly higher robustness was achieved, by for example, operation at very low power density.

The three parameters are referred to as the degradation standards.

3 Content of durability test

Three types of tests must be applied to characterize the durability of SOFC stacks. The three tests are: 1) long term test at constant conditions; 2) load cycling and 3) temperature cycling. The effect of these tests will be measured according to the degradation standards at the designed operating conditions (DOC) before and after the tests.

3.1 Constant conditions

The stack must be run continuously for 3000 hours at DOC.

3.2 Load cycles

The stack is load cycled 200 times with boundary conditions defined by the manufacturer. The boundary conditions include information of the upper and lower limits of the load cycle, reported as max. and min. current [A] for the stack. Rate of the load cycle must be reported as [Ampere/minute] and fuel/air utilization shall be reported in [%] for the respective loads.

3.3 Temperature cycles

The stack is exposed to a temperature cycle 25 times from DOC to room temperature. For each cycle the stack temperature must pass below 50°C. The rate of temperature cycling from operating temperature to room temperature (<50°C) and from room temperature to operating temperature shall be given in Kelvin pr. minute [K/min.]. Finally the procedure of a shutdown must be given.

4 Reporting durability

The effect of all parts of the durability test - long term testing at constant conditions, load cycles, and temperature cycles shall be measured as a change in performance relative to the design operating condition.

- ΔASR must reported as change in ASR pr. thousand hours [$\text{m}\Omega\text{cm}^2/\text{kh}$]
- ΔP must be reported as change in Power Density pr. thousand hours [mW/kh]
- ΔV_c must be reported as change in voltage pr cell, V_c , pr. thousand hours [mV/kh]

A %-wise change must also be given for all three degradation standards both in a graph and as a table value.

4.1 Examples

4.1.1 Reporting DOC

The designed operating conditions shall be reported in a table, see example below.

Current Density	T_furnace	T_air-inlet	T_fuel-inlet	FU	AU	Fuel composition		Air composition	
[A/cm^2]	[°C]	[°C]	[°C]	[%]	[%]	H ₂	CH ₄	O ₂	H ₂ O
						[mol%]	[mol%]	[mol%]	[mol %]

4.1.2 Reporting ΔV_c

In figure 1 an example of how data should be presented for ΔV_c . Linear regression is used to estimate $\Delta V_c = 20.2 \text{ mV}/\text{kh}$ and a relative change of $re/\Delta V_c = 2.5\%$ for cell in a stack tested in a shorter test of 1600 hours. The stack must be run continuously for 3000 hours at DOC.

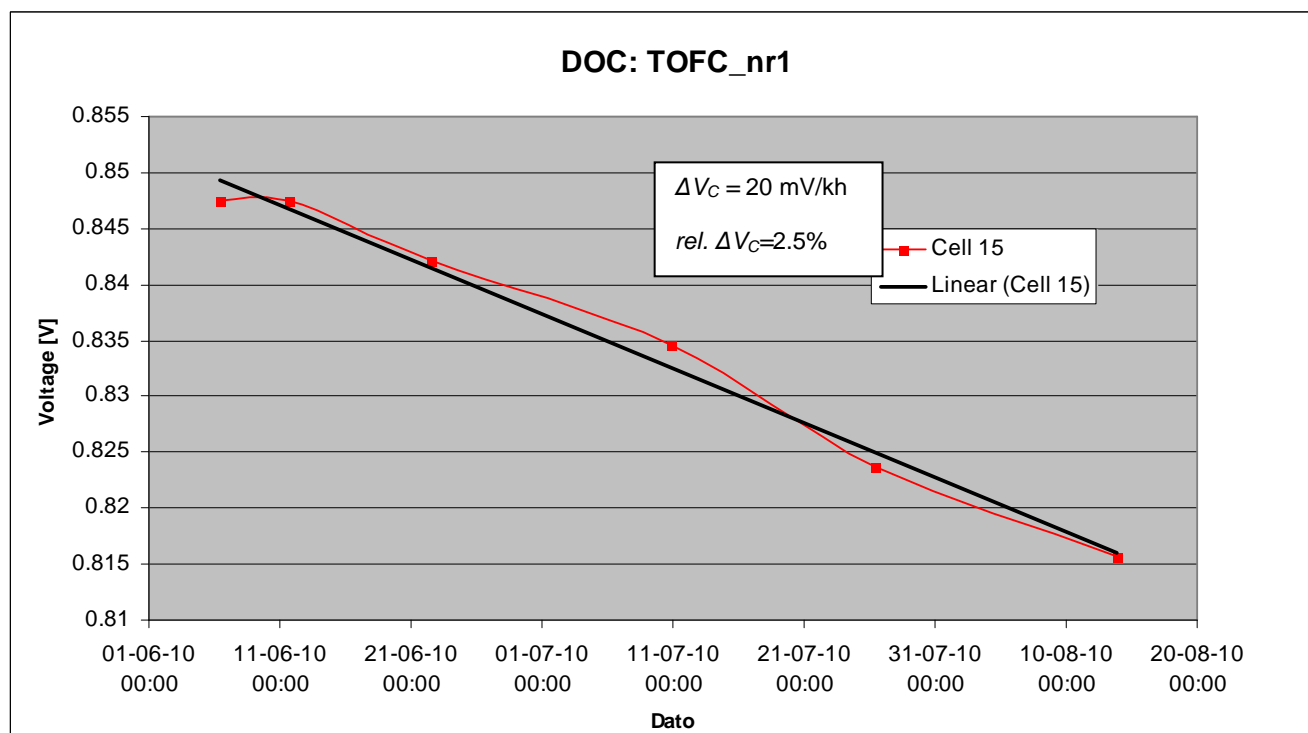


Figure 1. Example of estimated ΔV_c in degradation test for 1600 hours.

4.1.3 Reporting standards

The degradation standards are summarized in a table for the three durability tests defined in section 3 **Content of Durability Test**.

Initial degradation standards			Change in degradation standards			Relative change in standards		
V	P	ASR	ΔV_c	ΔP	ΔASR	rel- ΔV_c	rel- ΔP	rel- ΔASR
[V]	[W/cm ²]		[mV/kh]	[mW/cm ²]	[mΩcm ² /kh]	[%]	[%]	[%]

5 Definitions

5.1.1 Power Density

Power density shall be measured in [W/cm²] using the average power per cell [W] divided by the active area per cell A_{cell} in [cm²]. The power is the product of the measured current I and measured cell voltage potential V_c .

$$P_{\text{Density}} = \frac{I \cdot V_c}{A_{\text{cell}}}$$

5.1.2 Electrical potential

The cell voltage potential V_c shall be measured in [mV/cell].

5.1.3 Area Specific Resistance

The area specific resistance (ASR) shall be measured in [$\Omega \cdot \text{cm}^2$]. ASR is resistance of cell, R [Ω], normalized by its area, A [cm^2], so $ASR = R \cdot A$. The resistance of the cell is the difference between the average electromotive force pr cell (emf) and the cell voltage potential (V_c) divided by the measured current (I).

$$ASR = \frac{emf - V_c}{I} A$$

Based on relevant temperature, flow geometry, current density etc the averaged emf over the cell at operation can be estimated with a simple model. Topsoe Fuel will provide this model to the test center.

5.1.4 Electrical efficiency

Electric efficiency η_{el} shall be reported in percent measured according to [Larminie & Dicks], using the lower heating value LHV ,

$$\eta_{el} = \mu_f \cdot \frac{V_c}{LHV} \cdot 100\% .$$

The lower heating value, LHV , is 1.25V for the conversion of hydrogen and oxygen into water (liquid). V_c is the cell voltage potential. The fuel utilisation coefficient, μ_f , can be defined as

$$\mu_f = \frac{\text{mass of fuel reacted in cell}}{\text{mass of fuel input to cell}} .$$

5.1.5 Fuel- and air-utilization

The fuel and oxidant utilization, FU and AU respectively, shall be reported in [%]. Thus

$$FU = \mu_f \cdot 100\% \text{ and } AU = \mu_a \cdot 100\%$$

The utilization is the percentage of the supplied fuel or oxidant that is used in the electrochemical reaction (not i.e. burning of fuel due to stack leakage).

5.1.6 Current density

The current density shall be measured in Ampere pr. active cell area [A/cm^2].

5.1.7 Fuel Composition

The fuel composition must be reported in [mol%] for the different constituents of the fuel/air gas.

6 Bibliography

[Larminie & Dicks] “Fuel Cel Systems Explained”, James Larminie and Andrew Dicks, 2nd Edition, Wiley

Appendix D

Test standard draft – SOFC life-time prediction
July 2012

Test standard draft – SOFC lifetime prediction

This text is suggested to be added/supplement the text in sections “10.4 Long term durability test” and “10.5 Thermal cycling durability test” in IEC 62282-7-2 Ed.1: Fuel cell technologies – Part 7.2: Single cell/stack-performance test methods for solid oxide fuel cells (SOFC). The text in italic is comments and background to the suggested test procedure.

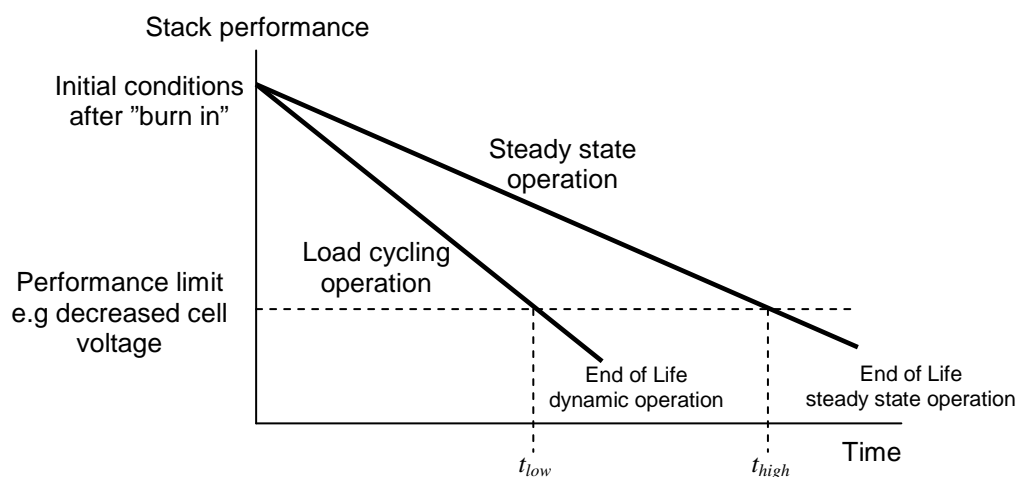
Approach

- 2 types of tests, steady state and dynamic (load and thermal cycling)
- Compressed, not accelerated testing

Lifetime definition

The lifetime is defined as the time to reach a specified degradation level. The end of life for the stack is assumed to be beyond the lifetime predicted in these tests. The tests for degradation and lifetime prediction shall be application independent. That means that the predicted lifetime is only valid as comparative value for stack manufacturers and system integrators. The changes in stack internal resistance, power output and cell voltage are measured during the tests. The stack lifetime can then be predicted for all measured properties, and the limit is specified by the system integrator. The tests provide data for the calculation/prediction of the time to reach this performance/lifetime limit set by the system integrator.

Tests are performed with steady state nominal load and rapid load cycling between nominal load and a mix of stand-by/minimum load and thermal cycles. These degradation tests will result in an upper t_{high} and lower t_{low} lifetime prediction representing worst case and favorable operating conditions. The sensitivity to dynamic stack operation is reflected in the difference between these lifetime limits.



Background

A lifetime definition that predicts the time until stack failure/end of life due to rapid degradation is not really a useful tool. Other performance factors such as reduction in power output or cell voltage are more important. The operational/load pattern is also of large importance for the lifetime. This pattern may be very different between installations. Future work, that not necessarily has to be within the standardization framework, may include a model that predicts the lifetime more precisely based on the type of application and load pattern.

A fuel cell cogeneration unit for example operates within a wide range of possible operating conditions, from continuous nominal load operation in a base load installation to a strictly electric load following operation.

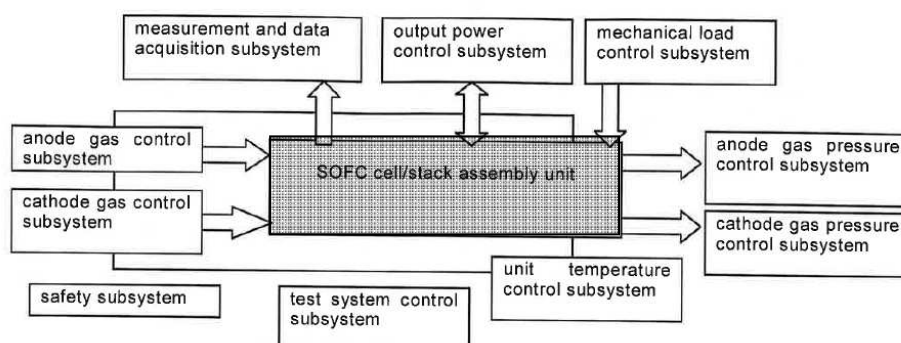
System boundary

The stack is tested as it is delivered to the system integrator, either as the stack only or as a part of an integrated system including fuel processing and other balance of plant parts. Text needed in case fuel processing etc. is not included.

At least x samples shall be tested for the steady-state and the dynamic tests respectively.

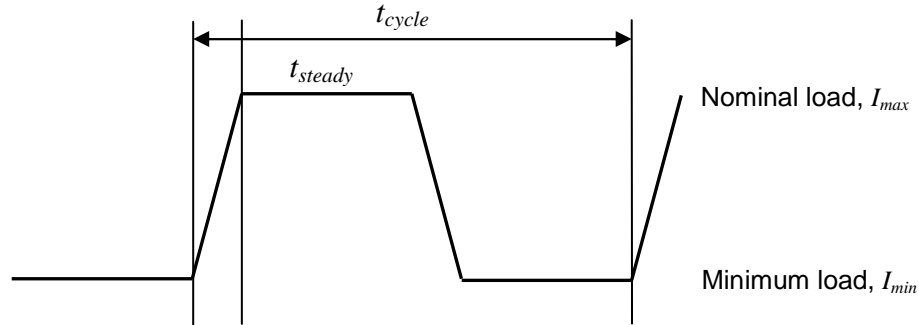
Background

The system boundary cannot always be limited to the stack itself. Some stack manufacturers will probably market both fuel cell stacks and fuel cell stacks integrated with parts of the Balance of Plant (BoP) components. The complexity in the determination of system boundary is indicated in the figure. The test procedure has to be defined in order to include both tests of the stack alone and an integrated package.



Acceleration method

The stack manufacturer specifies the nominal and minimum load (stack currents I_{max} and I_{min}), a maximum stack current load change rate τ (e.g. A/s), and also the shortest time for steady state conditions to be established in the stack. This may be equal for minimum and nominal load. Similar approach is applied for a thermal cycle.



The load cycle time t_{cycle} is then determined as

$$t_{cycle} = 2(I_{max} - I_{min})\tau + 2t_{steady}$$

The steady-state test shall have a duration of at least 4,000 hours (to be discussed). The number of cycles in the test shall not be less than 200 (to be discussed). Each cycle consists of 20 (to be discussed) load cycles followed by one thermal cycle.

Background

It is considered that compressing the load pattern is currently a more reliable tool than accelerating through for example increased stack temperature for the lifetime prediction. Degradation caused by for example increased stack temperature and/or stack current cannot be excluded to imply processes that not are present in the real on-site operation.

Data and data acquisition

No changes suggested.

Background

The data acquisition and presentation shall not differ from the IEC 62282-7-2.

Use of data for lifetime prediction

Plot the stack performance parameter chosen as function of the operating time. This is done for each 250/500 hours of operation. The time for the load cycles is the load cycle time multiplied by the

number of cycles. Use at least 75%(?) of the test time results to calculate the degradation rate using the first and last measurement in the interval chosen. Plot the stack performance parameter chosen for the lifetime prediction as a linear(?) function of time with initial value equal to the value after initial degradation.

Appendix E

Assessing durability of SOFC stacks
2nd Int. workshop on Degradation Issues of Fuel Cells
Thessaloniki, Greece
September 2011

Assessing durability of SOFC stacks

Anke Hagen

Head of Programme

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Risø DTU

Rasmus Barfod

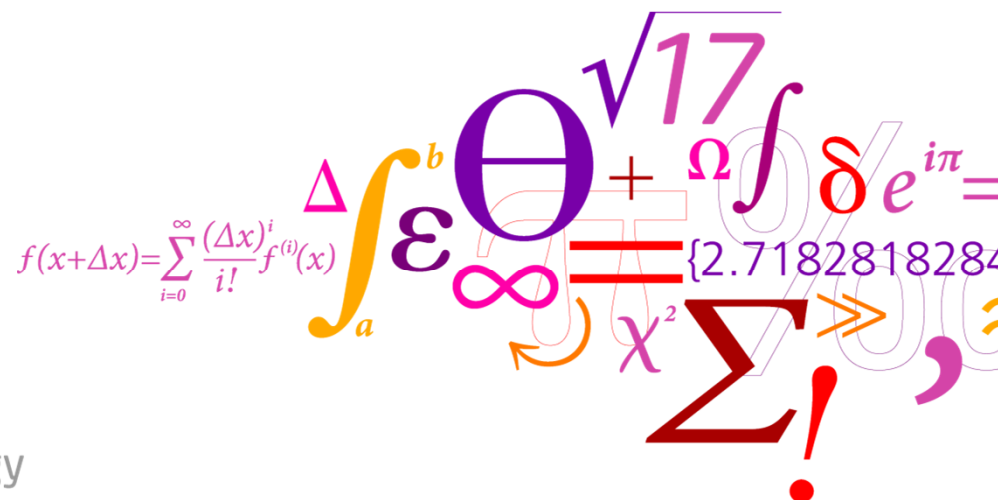
Topsoe Fuel Cell

Mikael Näslund, Henrik Iskov

Danish Gas Technology Centre

Risø DTU

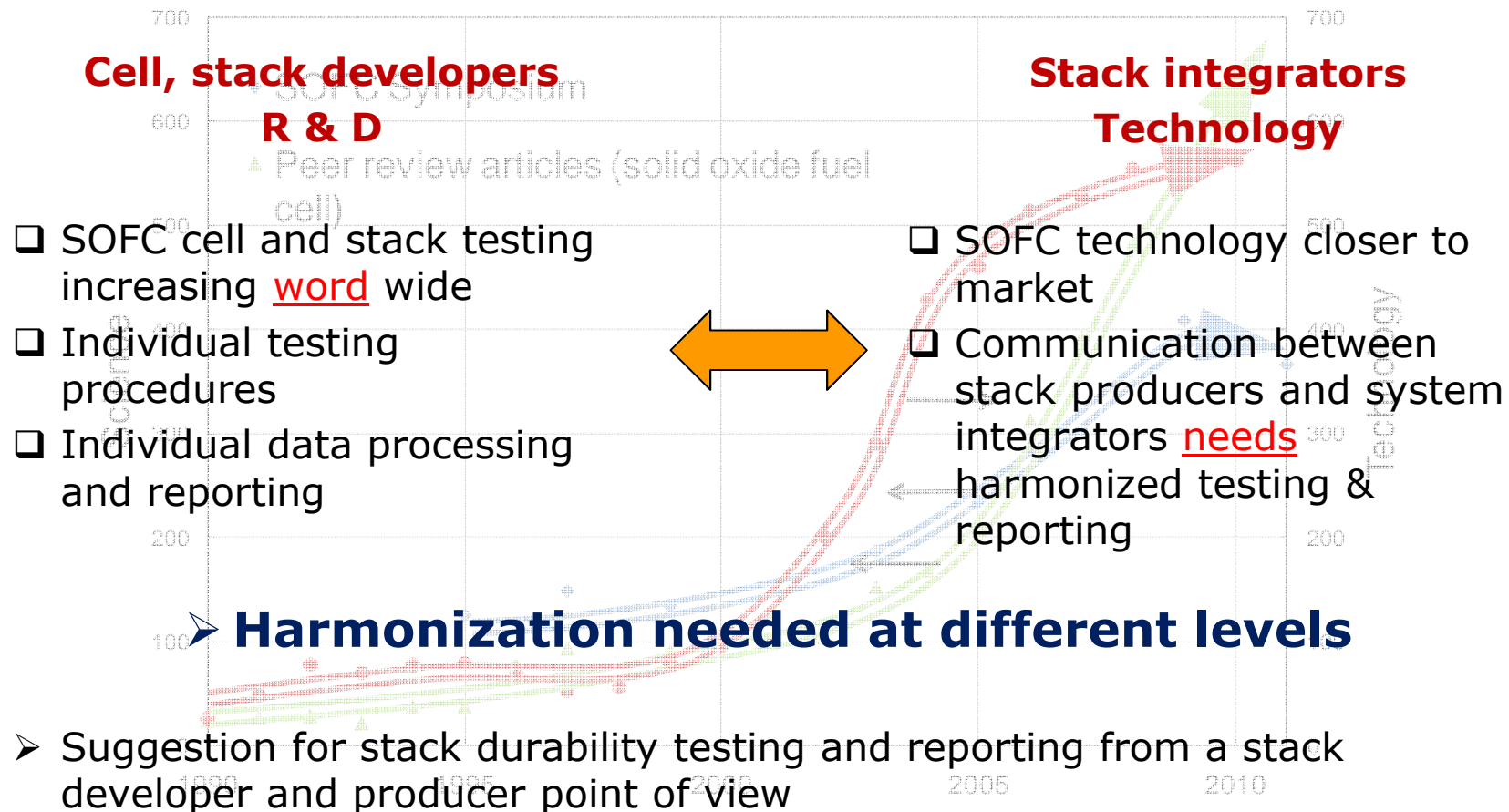
National Laboratory for Sustainable Energy



Outline

- ☐ Background & Motivation
- ☐ Durability of SOFC stacks
 - ☐ Testing
 - ☐ Reporting
- ☐ Discussion

Background & Motivation



Sources:


- Web of knowledge
- http://worldwide.espacenet.com/advancedSearch?locale=en_EP

Harmonization and standardization of tests

- ❑ Previous projects have been dealing with harmonization of testing on different levels and extents, e.g.

- ❑ FCTESTNET 

- Cells and short stacks
 - Systems
 - Stationary, portable, transport
 - PEMFC, MCFC, SOFC

- ❑ REAL SOFC 

- ❑ ...

- ❑ Interest for single cell/stack performance test standard for SOFC

- ❑ Proposal of standard from Japan

- **Such activities need to be reinforced**
 - **Having the anticipated users in mind**

Objective

- ☐ Harmonized procedure for durability testing
- ☐ Leaving freedom for stack specifications and technology areas (i.e. not pre-defined T , i , etc.)
- ☐ Providing reliable and comparable data
- ☐ Ease of communication and data exchange between manufacturers and customers
- ☐ Provide system integrators sufficient data to choose best stack for specific application

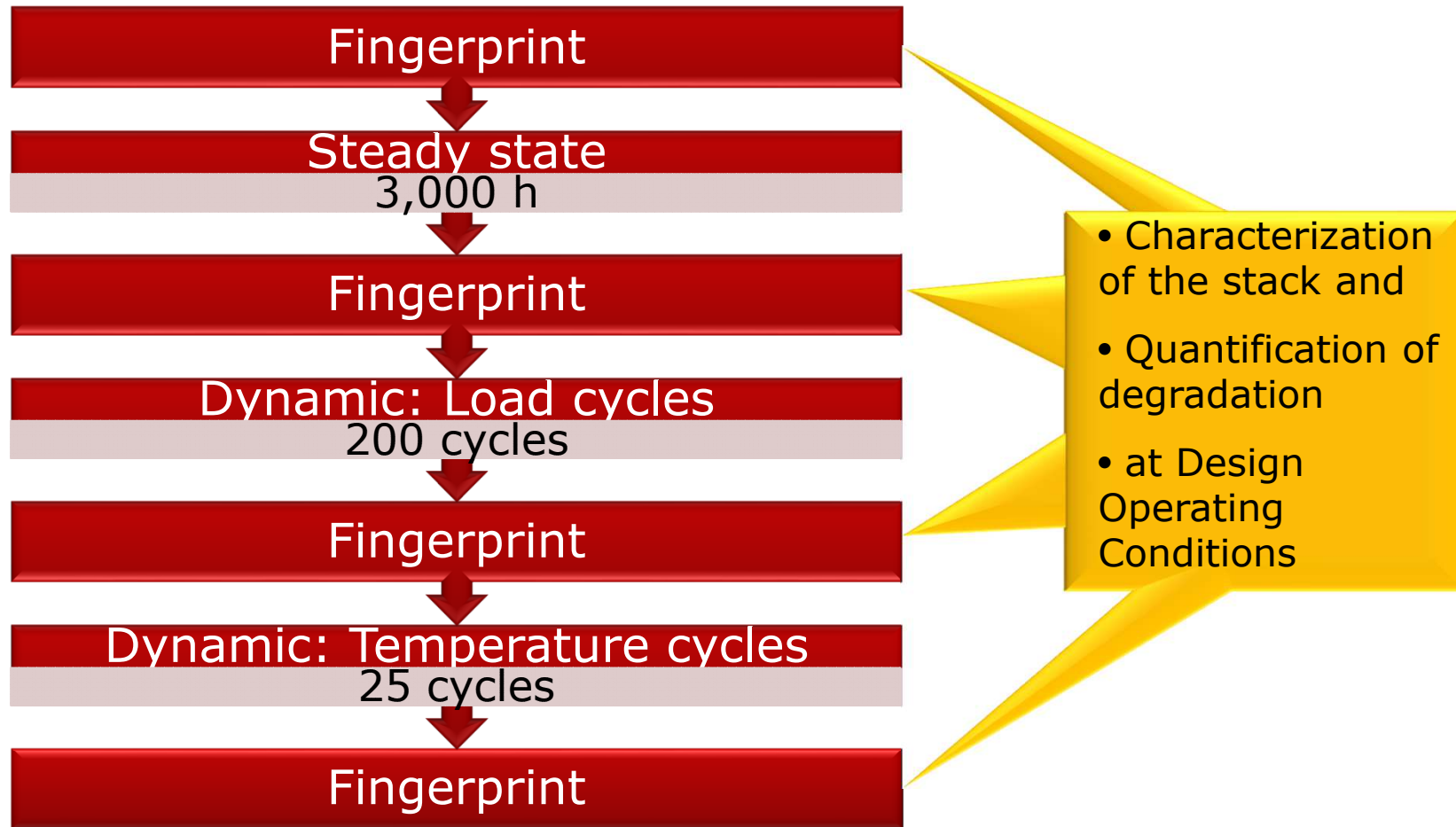
Setting the scene

- ❑ Aim is to be able to provide
 - Relevant information
 - For relevant operating conditions (e.g. μ CHP with different requirements in different countries)
- ❑ System boundary:
 - Stack
 - Stack including some parts of the balance of plant parts (BoP)
- ❑ Operating boundary:
 - Within the limits defined by the stack manufacturer (for example operating temperature, load change gradients and fuel composition)

Proposed SOFC stack durability tests

- ❑ Defines the test content (test sequences), not specific conditions.
- ❑ Manufacturer specifies a design operating point - a nominal operating point (DOC designed operation condition) which is used as reference to determine degradation rate and as reference when setting conditions for durability tests. It normally corresponds to the operating conditions in the real applications.
- ❑ Testing is performed at this DOC.
- ❑ It is acknowledged that even same application can require different durability specifications when established in different countries (e.g. load following or more or less constant operation for μ CHP). The stack receiver will be able to decide about the optimal stack based on the durability data.

Suggested testing sequence for durability



Reporting of results for durability

- ☐ Degradation as the change in power density, electric potential, and area specific resistance (ASR) over time in order to give a comprehensive representation of stack durability.
- ☐ By reporting these three degradation representations, it will e.g. be transparent if a significantly higher robustness was achieved, by for example, operation at very low power density
- ☐ Both table and graph

Example for reporting of results for durability

Operating conditions:

Current Density	T(furnace)	T(air-inlet)	T(fuel-inlet)	FU	AU	Fuel composition		Air composition	
[A/cm ²]	[°C]	[°C]	[°C]	[%]	[%]	H ₂ [mol%]	CH ₄ [mol%]	O ₂ [mol%]	H ₂ O [mol %]

Durability data:

Initial degradation standards			Change in degradation standards			Relative change in standards		
<i>V</i>	<i>P</i>	<i>ASR</i>	<i>V</i>	<i>P</i>	<i>ASR</i>	<i>rel- V</i>	<i>rel- P</i>	<i>rel- ASR</i>
[V]	[W/cm ²]	[Wcm ²]	[mV/kh]	[mW/cm ² /kh]	[mWcm ² /kh]	[%]	[%]	[%]

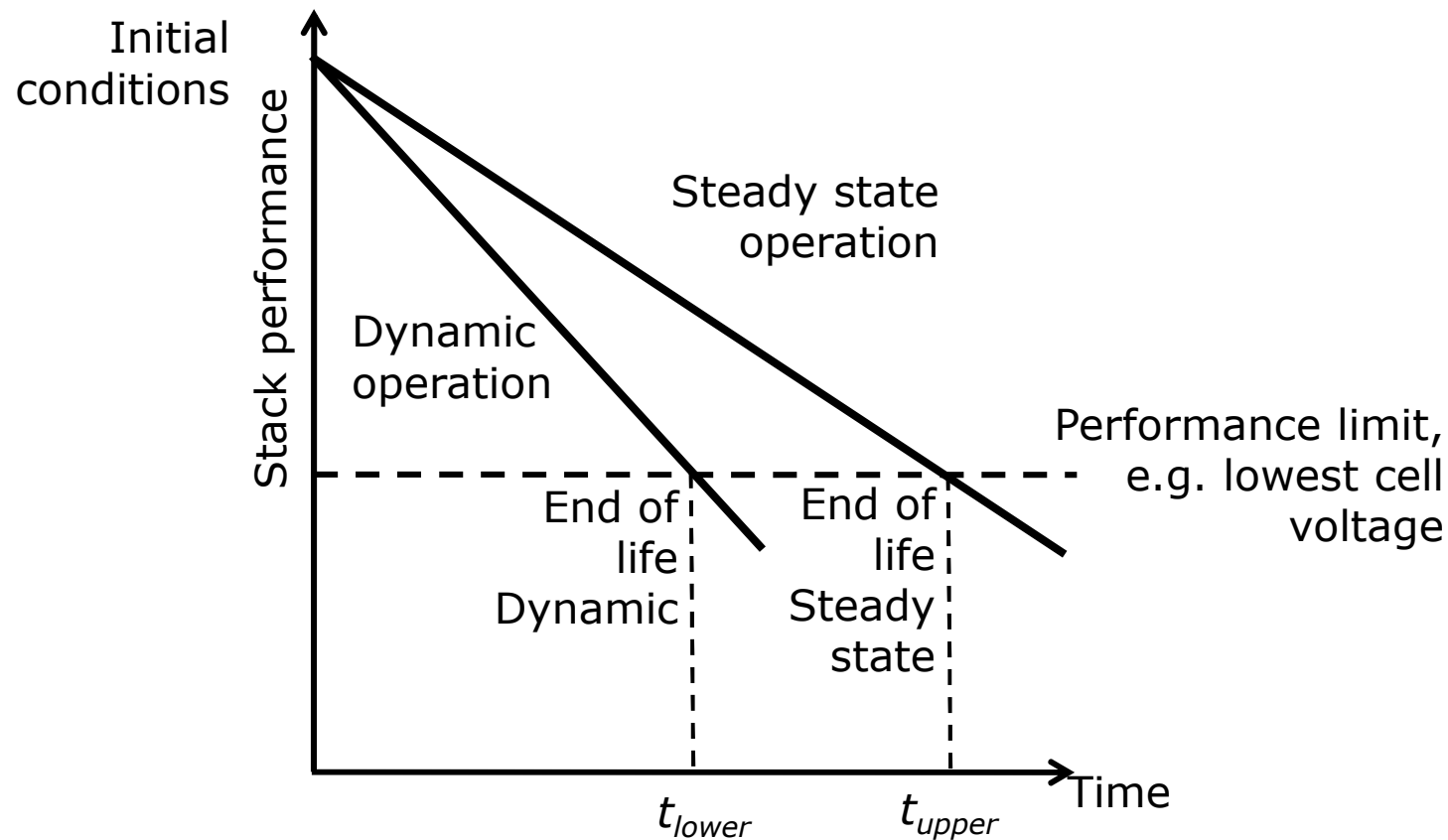
End of life of SOFC stack

- ☐ No life-time definition is suggested here as system integrators have different performance limits for the end-of-life definition (for example maximum voltage degradation, maximum stack internal resistance (strongly correlated to the efficiency) or lowest acceptable power output (for example 1 kW power output)).
- ☐ The tests shall provide degradation data for the integrator to calculate the life time for a certain application.

Accelerated testing?

- ❑ No real acceleration in terms of for example increased temperature and/or current (compared to DOC) is planned. It is unclear what the consequences are due to acceleration; what is improved and what is deteriorated?
- ❑ A steady state test segment and a dynamic test segment, including (rapid) load and thermal cycles are used, which might give faster degradation.
 - It is more likely that the tests can be labeled as compressed.
- ❑ The test will provide data for an upper (t_{upper}) and lower (t_{lower}) life time prediction, representative for a steady state and a highly dynamic operation.

End of life of SOFC stack



Discussion

- ☐ Procedure for assessment of durability of stacks for different application areas is suggested
- ☐ Strong focus on comparability of data and usability from a system integrator point of view
- ☐ At this point, no rigid operating conditions are specified, are to be defined by stack manufacturer
- ☐ Is there common interest and if yes, how strong, to pursue such a procedure further

Myndighedshåndtering for stationære brint og brændselscelleprojekter uden- for procesindustrien

Vejledning

Kunderapport

Juli 2012

Myndighedshåndtering for stationære brint- og brændselscelleprojekter udenfor procesindustrien

Vejledning

Henrik Iskov

Titel : Myndighedshåndtering for stationære brint og brændselscelleprojekter udenfor procesindus-
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Sagsnummer : 734-90; Dokument2

Sagsnavn : Testcenter for brint og brændselsceller

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1 Indledning

Denne vejledning er en af aktiviteterne i DGC og DTU's fælles testcenter for brint og brændselsceller, fase 1. Målet er at samle en fælles kortfattet vejledning omkring myndighedshåndtering af enheder eller projekter med brint eller brændselsceller.

2 Gyldighedsområde

Generelt gælder at vejledningen sigter på ikke industrielle anlæg med brint eller brændselsceller placeret i Danmark.

Vejledningen omfatter myndighedshåndtering eller godkendelse af

- Apparater baseret på brændselsceller, brint- eller naturgasfyrede
- Mindre anlæg til brintfremstilling
- Mindre lokale anlæg til distribution af brint
- Installation med brændselscelleanlæg
- Installation med brintproduktion

2.1 Afgrænsning

Der er tale om en uofficiel vejledning, der skal betragtes som en samling af gode råd i forbindelse med myndighedshåndtering af stationære projekter med brændselsceller eller lokal mindre brintproduktion, fx fra elektrolyseanlæg eller mindre reformere. Mikro fuel cells, dvs. anlæg op til 240 VA såvel som bærbare anlæg er ikke medtaget i nærværende oversigt, da disse anlæg typisk er transportable. Øvre grænse i standarder for fuel cells til kraftvarme er 70 kW indfyret (baseret på nedre brændværdi). For brintproducerende enheder som elektrolyseanlæg og reformere er der i de omtalte standarder typisk tale om enheder på under 400 Nm³/h.

3 Relevante myndigheder og bemyndigede instanser/ notified bodies

3.1 Myndighedskrav

Myndighedskravene kan opdeles i:

- Krav, der gælder for selve enheden (fx brændselscelle plus evt. reformer). Disse krav vil typisk være håndteret via en CE certificering af enheden.
- Krav til indretning og drift på opstillingsstedet.

3.1.1 Arbejdstilsynet

Arbejdstilsynet vil primært være involveret omkring maskindirektivet og trykdirektivet, dvs. i praksis de relaterede danske bekendtgørelser. Ofte vil disse aktiviteter være håndteret af bemyndigede organer.

3.1.2 Sikkerhedsstyrelsen

Sikkerhedsstyrelsen står bag Gasreglementet og håndterer i samarbejde med lokale gasselskaber (bemyndigede) kontrol og godkendelse af gasinstallationer. Afhængigt af

- Trykniveau
- Gastype
- Komponenttype

er enten Sikkerhedsstyrelsen eller Arbejdstilsynet eller begge instanser (deres bemyndigede organer) involveret i en godkendelse, se nedenfor.

3.1.3 Arbejdstilsynet eller Sikkerhedsstyrelsen eller begge?

Nedenfor er forsøgt at lave en oversigt over forholdene med hensyn til anlæg med naturgas eller brint.

Oversigten baserer sig delvis på foreløbigt materiale præsenteret på en konference i foråret 2012 af Sikkerhedsstyrelsen. Materialet er ikke endeligt afhandlet med Arbejdstilsynet og må derfor kun betragtes som en indikation af fremtidens forventede relationer mellem Sikkerhedsstyrelsen og Arbejdstilsynet indenfor området.

Det bemærkes, at naturgassystemer allerede fra tryk over 100 mbar medfører involvering af Arbejdstilsynet. Brintbærende anlæg medfører først involvering af Arbejdstilsynet ved tryk over 500 mbar.

- < 100 mbar: Naturgas distributionssystemer godkendes af Sikkerhedsstyrelsen (SIK) iht. Gasreglementet (GR)
- > 100 mbar: Naturgasanlægs trykbærende dele skal iht. Bek. 414:1988 godkendes af Arbejdstilsynet (AT)
- < 500 mbar: Brintbærende anlæg skal godkendes efter GR iht. ny medio 2012) samarbejdsaftale mellem SIK og AT.
- > 500 mbar: Brintbærende anlæg skal godkendes efter GR og AT iht. ny (medio 2012) Samarbejdsaftale mellem SIK og AT.
- < 16 bar: Naturgas stikledninger og forbruger naturgas installationer skal godkendes efter GR.
- > 16 bar: Naturgas stikledninger og forbruger installationer skal godkendes af AT.

3.1.4 Beredskabsstyrelsen

For større gaslagre skal der ske godkendelse af Beredskabsstyrelsen. For mindre gaslagre er det det kommunale redningsberedskab, der godkender. Mere herom i kap. 6.2.5.- 6.2.7.

3.1.5 Kommune (redningsberedskab/brandberedskab, byggesag og miljøgodkendelse)

3.2 Bemyndigede organer (eksempler)

3.2.1 Dansk Gasteknisk Center

DGC er af Sikkerhedsstyrelse bemyndiget/ akkrediteret til at teste, kontrollere dokumentation og certificere/godkende apparater iht. GAD (2009/142/EEC) og kedelvirkningsgradsdirektivet (BED, boiler efficiency directive) (92/42/EEC)

3.2.2 Force Technology og Jebru

Force og Jebru er af Arbejdstilsynet bemyndiget til at teste, kontrollere dokumentation og certificere/godkende anlæg iht. Trykdirektivet.

3.2.3 Det lokale gasdistributionsselskab

Varetager normalt på vegne af Sikkerhedsstyrelsen myndighedsgodkendelser i relation til Gasreglementet, herunder den supplerende vejledning for installation af brintforbrugende anlæg. Da brintbærende anlæg udenfor procesindustrien stadig er noget forholdsvis nyt, vil Sikkerhedsstyrelsen ofte direkte medvirke i processen.

4 Godkendelse af gasapparater

Med apparater forstås udstyr der leveres som en enhed fra fabrikanten. Apparater skal være udformet, så de overholder gældende lovgivning, dvs. relevante EU direktiver og eventuel national lovgivning. Bemærk at aftræksrørsystemet i Danmark af myndighederne betragtes som en del af enheden og skal derfor godkendes eller CE mærkes sammen med enheden.

Apparater i EU skal generelt være CE mærkede, dvs. der skal foreligge en fabrikanterklæring (CE overensstemmelseserklæring) om at apparatet overholder alle relevante direktiver. Alle disse direktiver anføres på erklæringen. Normalt gælder at fabrikanten selv kan udarbejde CE erklæringen uden nogen myndighedskontrol. For visse potentielt farlige apparatgrupper som fx gasapparater gælder, at en bemyndiget instans/notified body skal gennemgå apparat- dokumentation og test (eller selv teste) af enheden for verifikation af at direktivernes væsentlige sikkerhedsmæssige krav er overholdt. Test kan enten ske hos bemyndiget instans eller foregå hos producent under overvågning af bemyndiget instans.

CE godkendelse kan ske i form af

- typetest eller
- enhedsverifikation

Enhedsverifikation vælges typisk, når der er tale om en enkelt enhed eller en afgrænset produktion (batch). Forskellen til typetest er alene, at man ved typetest også har en periodisk produktionskontrol.

5 Godkendelse af projekter og installationer

5.1 Generelt

Generelt gælder at man så tidligt som muligt i projektforsløbet bør tage kontakt til relevante myndigheder for at drøfte projektet. Visse godkendelsesforsløb kan ofte være bestemmende for, hvornår et anlæg kan idriftsættes, dvs. at godkendelsen kan være den længst varende aktivitet. Det ses især ved større kraftværksprojekter, men også projekter med væsentligt gasoplag kan have et langstrakt godkendelsesforsløb.

En af fordelene ved tidligt at koble myndighederne ind på projektet, er at deres krav ofte er billigere at inkorporere på dette tidspunkt, hvor meget endnu er åbent og fx hovedkomponenter ikke er ordret.

5.2 Risikoanalyse

Myndighederne stiller generelt krav om at en installation er sikker – både for driftspersonale og omgivelser. Til eftervisning heraf vil en systematisk risikoanalyse af installationen som regel være et effektivt værktøj. Systematisk risikoanalyse er oprindeligt udviklet til anvendelse i forbindelse med større potentielt risikable anlæg, som visse procesanlæg og atomkraftværker. Efterhånden er de blevet mere almindelige. Fx er det et krav i Maskindirektivet, at der skal udføres risikoanalyser. En analyse kan dog udføres på mange niveauer og i forskellige faser af et projektforsløb.

En typisk fremgangsmåde kunne være: Man udfører en indledende analyse af designet og finder herved ofte nogle svagheder, hvor designet skal ændres. Herefter udføres en fornyet analyse osv. frem til det endelige design. Ligeledes udføres risikoanalyser af driftsforhold som opstart og nedlukningsprocedurer samt analyser af nødprocedurer.

I ”rigtige” risikoanalyser sættes vurderede sandsynligheder på alle tænkelige hændelser, og der opstilles risikotræer for mulige hændelsesforsløb, hvor der kan beregnes sandsynligheden for en vilkårlig hændelse. Ud fra krav til hvor stor en risiko, der kan accepteres (fx for en alvorlig ulykke på et A kraftværk), ændres og genberegnes på systemet, indtil ingen hændelser har en sandsynlighed, der overstiger den ønskede værdi.

For mindre og enklere anlæg anvendes ofte en mere enkel analyse, hvor man undlader at sætte (spekulative) sandsynligheder på hændelserne, og derfor heller ikke regner på de kombinerede sandsynligheder.

5.3 Installationskrav

Installationskrav vil komme fra følgende instanser

5.3.1 Kommunen

- Byggetilladelse
- Miljøgodkendelse
- Brandberedskab: Brandberedskabet stiller krav til zoneklassificering, brandmæssig indretning og gasoplag. Endvidere kræves udarbejdet en nødbereidskabsplan.

5.3.2 Gasforsyningsselskab

Dette kan være det lokale naturgasforsyningsselskab eller gasleverandør. Såfremt der er tale om lokalt produceret gas, vil producenten være ansvarlig iht. Gasreglementets særlige krav til gasleverandøren. Se 3.3.1 vedr. opdeling mellem Gasleverandør og Arbejdstilsyn.

5.3.3 Arbejdstilsyn eller bemyndiget organ

Udover arbejdsforhold håndterer Arbejdstilsynet krav relateret til overholdelse af maskindirektivet, trykdirektivet og Atex direktivet. Der henvises til relaterede danske bekendtgørelser.

5.4 Nødbereidskabsplan

5.4.1 Generelt

Nødplaner og procedurer bør udarbejdes i samarbejde med det lokale brandberedskab.

Organisering af internt nødbereidskab bør foretages, ligesom øvelser jævnligt bør foretages.

5.4.2 Brintudslip

Man skelner mellem små lækager og store lækager. Små lækager defineres som lækager, der umiddelbart vurderes som uskadelige. Der bør dog ligge

på forhånd fastlagte procedurer for afhjælpning. Større lækager kræver tiltag som:

- afbrydelse af brinttilførslen
- evakuering af området
- tilkaldelse af brandvæsen

Hvis fx en gasbeholder lækker, bør man ikke forsøge tætning; men i stedet om muligt flytte beholderen ud i det fri, hvor den tømmes før afhjælpning af utætheder forsøges.

5.4.3 Brandslukning

En brintbrand bør normalt ikke forsøges slukket, før brinttilførslen er stoppet. Der er nemlig stor fare for genantændelse eller eksplosion.

Vand, CO₂ eller pulverslukkere kan bruges. Pulverslukkere har den fordel, at de gør flammerne mere synlige.

Brand i en brintbeholder bør kun forsøges slukket, såfremt den er placeret i et åbent eller stærkt ventileret område uden potentielle antændelseskilder. Normalt bør man ikke forsøge at flytte en brændende cylinder, men alene nedkøle omgivelserne med vand.

6 Lovgrundlag

6.1 EU direktiver

Følgende direktiver er typisk relevante for stationære brint eller brændselscelleprojekter:

6.1.1 Gasapparatdirektivet 2009/142/EC (GAD)

Gasapparatdirektivet gælder for gasfyrede apparater uafhængigt af gaskvalitet og type. Dvs. direktivet gælder også for rent brintfyrede anlæg. Dog skal der være tale om apparater til kogning, opvarmning, varmvandsproduktion, køling, belysning eller vask. For brændselscelleanlæg skal der være tale om anlæg til kraftvarme.

*Det skal bemærkes at apparater til industrielt procesbrug i industrien **ikke** er omfattet af gasapparatdirektivet.*

Der arbejdes pt. på at udvide gyldighedsområdet for GAD, så også anlæg der ikke anvendes til varmeproduktion, skal overholde GAD. Hidtil har disse anlæg været baseret på maskindirektivet. Baggrunden er, at de fleste gas-tekniske sikkerhedsproblematikker er ens for både varme- og ikke varme-producerende anlæg.

For brændselscelleanlæg til kraftvarmedrift med under 70 kW indfyret effekt findes de væsentligste krav i standarden EN 50465. Se mere i afsnittet vedr. standarder.

GAD indtager i øvrigt en særstilling, idet alle øvrige krav til apparatet fra andre relevante direktiver er integreret heri. Det betyder, at opfylder et apparat GAD vil alle øvrige relevante direktiver være overholdt.

6.1.2 Trykudstyrsdirektivet 97/23/EC (PED)

Trykudstyrsdirektivet vil være relevant for mindre procesanlæg som elektrolyseanlæg og reformerianlæg såvel som tankanlæg. Afhængigt af tryk og tryksat volumen i anlægget stilles større eller mindre krav til dokumentation af anlægget.

6.1.3 Elektromagnetisk kompatibilitets direktiv 2004/108/EF (EMC)

For de gasapparater, der er omfattet af GAD, gælder at EMC krav som nævnt er integreret i GAD. EMC direktivet kræver ikke ekstern verifikation af, hvorvidt direktivets krav er overholdt. Da der er tale om ret kompleks teknologi og ret investeringstunge testopstillinger, vurderer mange fabrikanter, at det ikke kan betale sig at investere heri, og derfor vælger de at anvende eksterne konsulententer til assistance omkring EMC direktivet.

6.1.4 Maskindirektivet 2006/42/EC

Maskindirektivet er relevant for alle brint og brændselscelleanlæg, der ikke er omfattet af Gasapparatdirektivet

6.1.5 Lavspændingsdirektivet 2006/95/EC

Gælder for eludstyr med en spænding på 50-1000 VAC eller 75-1500 VDC. Såfremt der er tale om udstyr, der er dækket af GAD vil forhold omkring lavspændingsdirektivet internt i apparatet, som tidligere nævnt, være indeholdt i GAD.

6.1.6 Direktiv om materiel i eksplosive atmosfærer 94/9/EC: ATEX direktivet

Direktivet er relevant hvor der kan opstå en potentielt eksplosiv atmosfære, dvs, der er

- Brændbar gas
- Ilt
- Temperatur fra -20 – 60 grader C og et tryk omkring 1 baro (0,8 – 1,1 baro)
- Mulighed for at flammefronten fra antændt gas kan brede sig til hele den brændbare gas

Såfremt der er tale om udstyr der er dækket af GAD vil ATEX forhold internt i apparatet som tidligere nævnt være indeholdt i GAD.

6.2 Nationale forskrifter og tilhørende vejledninger

6.2.1 Bygningsreglement (BR)

Bygningsreglementet omhandler krav til

- Indretning

- Konstruktion
- Brandforhold
- Indeklima
- Energiforbrug
- Installationer

6.2.2 Luftvejledning (Miljøstyrelsen)

Luftvejledningen redegør i detaljer for emissionskrav for anlæg af forskellige typer, størrelser og brændsler. Vejledningen redegør fx for

- BAT princip
- Beregning af skorstenshøjde
- Kontrolregler og metoder

For gasfyrede anlæg under 120 kW indfyret (v. nedre brændværdi) henvises til Gas- og Bygningsreglementerne. Større anlæg behandles i Luftvejledningen.

6.2.3 Gasreglementet (GR)

Gasreglementet beskriver krav til design og indretning af installationen. Fx

- Materialevalg
- Samlingstyper
- Ventilationsforhold
- Afgasforhold
- Afløbsforhold
- Systemopbygning
- Afstandskrav

Udover Gasreglementet, hvori en del af lovgivningen indenfor gasinstallationer er udmøntet, kan inspiration findes i standarden IEC 62282-3-3: Stationary fuel cell power systems - installation.

6.2.4 Sikkerhedsstyrelsens vejledning for installation af brintforbrugende anlæg (version juni 2011)

Der er tale om en supplerende vejledning i forhold til Gasreglementet, der konkret henviser til relevante dele af Gasreglementet. Herudover oplyses også om anden relevant lovgivning for brintforbrugende anlæg. Længere tids uklarhed mht hvilke grænser der gælder for hvornår Sikkerhedsstyrelsen/ Gasreglementet eller Arbejdstilsynet skal involveres er pt. ved at blive afdækket. Der henvises til kap. 3.1.3.

6.2.5 Bekendtgørelse om tekniske forskrifter for gasser (Bek nr. 230 fra 2011)

Denne bekendtgørelses krav er uddybet i nedennævnte vejledning, som det anbefales at tage udgangspunkt i.

6.2.6 Vejledning til tekniske forskrifter for gasser (Vejledning nr. 15 2010)

Vejledningen samler og forklarer en lang række tidligere forskrifter og bekendtgørelser om opbevaring af gasser. Fx udformning af lagerrum, ventilation, brandforhold og afstandskrav.

6.2.7 Vejledning om klassifikation af eksplosionsfarlige områder

Klassifikation af eksplosionsfarlige områder er væsentlig, da krav til udstyr og indretning og drift varierer stærkt efter hvilken klasse et område klassificeres som. Vejledning indeholder bl.a. en lang række vejledende eksempler på klassificering.

6.2.8 Nationale implementeringer af direktiver

For de i 6.1 nævnte direktiver forligger der tilsvarende nationale implementeringer.

7 Relevante standarder for brint og brændselsceller

7.1 Anvendelse af standarder

Formålet med standarder er at gøre det lettere at udbrede og anvende teknologi herunder handel og tilpasning til andet udstyr. De udarbejdes på vegne af fabrikantsammenslutninger mv.

Som udgangspunkt er det frivilligt om standarder overholdes – men *der gælder det princip, at såfremt der er udgivet harmoniserede internationale standarder vedr. sikkerhed indenfor et område, - ja så skal man enten overholde disse eller eftervise, at man mindst er på samme niveau.* Det betyder, at man ofte vil slippe lettest ved at følge en harmoniseret standard.

I forbindelse med fx gasfyrede enheder der ønskes CE godkendt, er det fabrikantens beslutning, om man ønsker at overholde standardens krav fuldt ud, eller man i samarbejde med den CE godkendende instans vælger at plukke de dele ud der relaterer sig til overholdelse af Gasapparatdirektivets væsentligste *sikkerhedsmæssige* krav.

I situationer hvor Lov om arbejdsmiljø gælder, kan der være tale om, at en standard *skal* følges, idet § 45 heri anfører, at såfremt der foreligger standarder, der har sikkerhedsmæssig betydning, så skal de følges. Da fx design-standarder for gasbaserede apparater bestemt må siges at have sikkerhedsmæssig betydning, så kan der være tale om, at visse standarder skal følges.

7.2 Overblik over internationale standarder

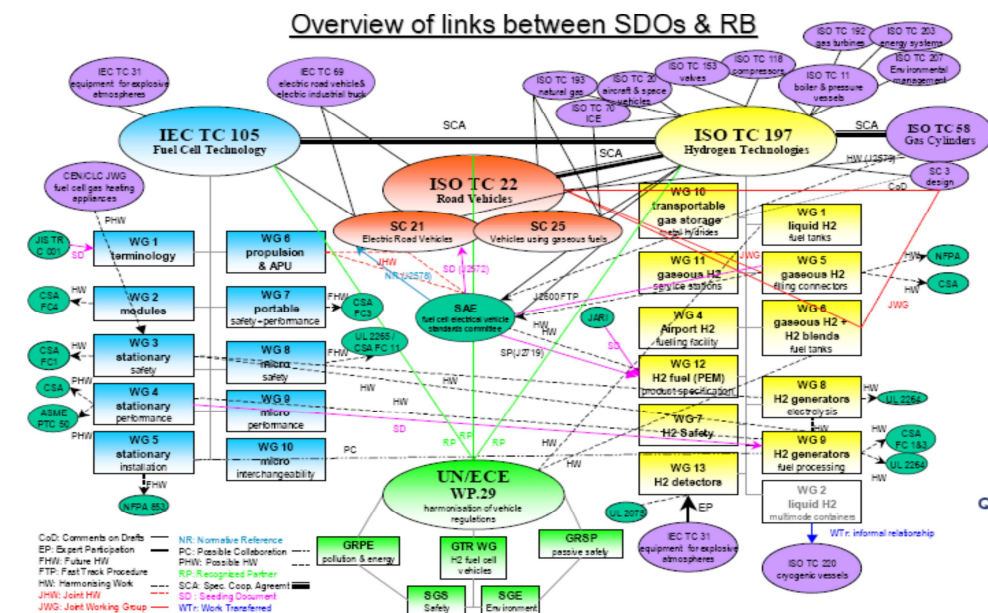


Fig. 1: Oversigt over sammenhæng mellem standardiseringsarbejdsgrupper for brint og brændselsceller.

IEC og ISO er internationale standardiseringsorganisationer, og CEN/CENELEC er en europæisk standardiseringsorganisation, der fx udarbejder standarder indeholdende de essentielle krav i et EU direktiv.

IEC TC 105 arbejder med standardisering af brændselsceller til både stationære og transportable formål, og ISO TC 197 arbejder med standardisering af brintteknologi i øvrigt. CEN/CENELEC arbejder med fortolkning af Gasapparatdirektivets krav til stationære brændselsceller til kraftvarme.

7.3 CEN/CENELEC

**GAD's krav til brændselscellebaserede mikro/mini kraftvarmeenheder:
CEN/CENELEC EN 50465:2008**

Fuel Cell gas heating appliance of nominal heat input up to 70 kW

Denne standard er CEN's forsøg på at tolke Gasapparatdirektivets essentielle krav for stationære brændselscelleanlæg til kraftvarmedrift. Det er sket på mandat fra EU kommissionen, og målet er en harmoniseret standard for EU. Bagerst i standarden findes det såkaldte ZZ-annex, der beskriver hvorledes

standarden opfylder Gasreglementet krav. Der arbejdes til stadighed med at nå frem til en harmonisering af standarden.

Denne europæiske standard vedrører forhold som

- Konstruktion
- Funktionskrav
- Sikkerhed
- Installation
- Effektivitet
- Ydelse
- Mærkning
- Testmetoder

Bemærk at i modsætning til Gasapparatdirektivet gælder denne standard kun for apparater fyret med gasser fra de tre gasfamilier bygas, naturgas og LPG i henhold til EN 437. Det betyder, at standarden ikke gælder for brintfyrede anlæg.

EN 50465 er på vej til at blive afløst af en udvidet standard, der pt. ligger i udkast som prEN 50465 ed 2. Den nuværende udgave dækker kun brændselsceller, men den nye udvidede udgave inddrager også andre mikrokraft-varmeteknologier som fx gas- og stirlingmotorer.

EN 50465 henviser til en lang række direktiver og andre standarder, hvoraf enkelte kun foreligger i udkast.

EN 50465 henviser til brændselscellestandarden IEC 62282-1 og 62282-3-1. IEC 62282-3-1 henviser til 62282-2 og 62282-3-2. Disse standarder er nu ved at blive afløst af reviderede og supplerende standarder beskrevet i det følgende.

EN 50465 er udgangspunkt for en ny international IEC 62282 standard, nemlig IEC 62282-3-400, se nedenfor.

7.4 CEN/IEC TC 105 Fuel cell technologies

Disse standarder ligger under den tekniske komite TC 105, der omfatter brændselscelleteknologi samt nu også mindre kraftvarmeteknologi.

I det følgende nævnes både eksisterende standarder, og standarder der er på vej, dvs. kun ligger i udkast. De fleste af disse udkast er tilgængelige, og det anbefales at orientere sig om indholdet i relevante standarder, uanset om de kun ligger i udkast, da der som regel er indarbejdet en stor mængde praktisk erfaring i disse standarder via arbejdsgruppernes input.

Den primære standard for brændselscelleteknologi er

IEC 62282 Fuel Cell Technologies

Generelt gælder at der i disse standarder ikke er nogen begrænsninger i anlægsstørrelse. Enkelte standarder gælder dog kun for begrænsede størrelser som fx 70 kW indfyret eller 10 kWe output.

IEC 62282 er opdelt i en række delstandarder:

Terminologi for brændselsceller:

IEC 62282-1 Ed.2(2010-04):

Terminology

En revideret udgave, Ed.3 udkommer snart.

7.4.1 Standarder for **sikkerhed**

Brændselscellemodul:

IEC 62282-2 Ed.2 (2012-03):

Fuel Cell Modules

Indeholder en række mindstekrav og tilsvarende tests af **ydelse og sikkerhed**. Standarden gælder for alle typer brændselsceller, som fx

- PEM
- SOFC
- Alkalinsk
- Molten Carbonate
- Fosforsyre

Standarden er netop (marts 2012) udkommet i en revideret udgave.

Sikkerhedsstandard for stationære brændselscelleanlæg:

IEC 62282-3-100 (2012-02):

Stationary fuel cell power systems – Safety

Afløseren til IEC 62282-3-1, der nu er udgået.

7.4.2 Standarder for ydelse

Brændselscellemodul: Se 7.4.1!

Ydelsesteststandard for SOFC enkeltcelle eller stak:

IEC 62282-7-2 Ed.1

Single cell/stack-performance test methods for solid oxide fuel cells (SOFC)

Forventes at udkomme i 2013.

Ydelsesteststandard for brændselscellestak PEM enkeltcelle:

IEC 62282-7 -1 Ed.1

Single cell test methods for polymer electrolyte fuel cells (PEFC)

Forventes at udkomme i 2013

Ydelsesteststandard for stationære brændselscelleanlæg:

IEC 62282-3-200 Ed.1 (2011-10):

Stationary fuel cell power systems – Performance test methods

Afløseren til IEC 62282-3-2, der nu er udgået.

Bemærk at standarden KUN gælder for stationære anlæg *over* 10 kWe.

Ydelsesteststandard for mindre (< 10kWe) stationære baserede brændselscelleanlæg:

IEC 62282-3-201 Ed.1:

Stationary fuel cell power systems – Performance test methods

Denne standard der pt. ligger i arbejdsudgave som committee draft for vote (CDV) version, dvs. et færdigdiskuteret udkast, der bare skal igennem en afstemningsrunde. Standarden forventes at udkomme medio 2013. De fleste gasformige eller flydende brændsler er inkluderet.

Bemærk at for standarden nu omfatter alle typer brændselsceller brændselscelleanlæg *under* 10 kWe.

Det skal endvidere bemærkes, at standarden forudsætter, at anlæggets primære produkt er el, og det sekundære produkt er varme.

7.4.3 Standarder for installation

Installationsstandard for stationære brændselscelleanlæg:

IEC 62282-3-3 Ed.1

Stationary Fuel cell power systems - Installation

De nationale installationskrav er beskrevet i Gasreglementet, og den særlige supplerende vejledning for brintforbrugende enheder ”Sikkerhedsstyrelsens vejledning for installation af brintforbrugende anlæg” fra juni 2011. IEC 62282-3-3 skal ses som et supplement til ovenstående.

Er nu på vej til at blive afløst af IEC 62282-3-300 Ed.1 Installation.

7.4.4 Standarder for sikkerhed, ydelse, installation ...

International udvidet udgave af EN50465 på vej: Standard for mikro/mini brændselscellebaserede kraftvarmeanlæg:

IEC 62282-3-400

Stationary fuel cell power systems – Small fuel cell systems with combined heat and power output

I forhold til EN 50465 gælder standarden for alle typer brændsler og alle typer drivende enheder, dvs. ud over brændselscelleenheder, gælder standarden også for motorer, turbiner, stirlingmotorer etc.

Standarden gælder for typetest i stil med den europæiske CE test/mærkning
Standarden omfatter:

Anlæg med under 70 kW input

Brændsler som

- Naturgas og andre metanrige gasser som bygas
- Olie derivater: Petroleum, LPG, propan, butan
- Alkoholer som methanol, ethanol
- Hydrogen

Varmeaftag vandbaseret.

Gælder for både indendørs og udendørs anlæg.

Gælder for anlæg med og uden batterier og med eller uden nettilslutning.

Standarden beskriver krav til

- Konstruktion
- Funktionskrav
- Sikkerhed
- Installation
- Effektivitet
- Ydelse
- Mærkning
- Testmetoder

Nationale krav vil være anført i et bilag.

Standarden forventes at udkomme i september 2014.

7.5 ISO TC 197: Hydrogen Technologies

TC 197 omfatter pt. 12 arbejdsgrupper, der behandler en række teknikområder af betydning for en brintbaseret transportsektor. I nærværende rapport vil vi kun omtale standarder, der er relevant for udformning af mindre brintproduktionsanlæg og brintforsyningsanlæg.

I modsætning til de store brintproduktionsanlæg, der typisk ses i olie- og gasindustrien, tænkes her på mindre, decentrale produktionsenheder til forsyning af en tankstation for brintkøretøjer eller et område med brintfyrede brændselsceller.

Myndighedskravene følger som udgangspunkt de tidligere beskrevne generelle krav for stationære gasbaserede anlæg.

7.5.1 Brintgeneratorer baseret på elektrolyse

ISO 222734-1:2008

Hydrogen Generators using water Electrolysis Process - Part 1: Industrial and Commercial Applications.

Standarden omfatter krav til

- Konstruktion
- Sikkerhed
- Ydelse

Standarden indeholder en lang række tests til verifikation af funktion, sikkerhed og ydelse.

For alle sikkerheds- og ydelsesparametre henvises i standarden til relevante teststandarder.

Standarden kan anvendes til certificering.

ISO/DIS 22734-2:2011

Hydrogen Generators using water Electrolysis Process - Part 2: Residential Applications.

Standarden omfatter krav til

- Konstruktion
- Sikkerhed
- Ydelse

Standarden indeholder en lang række tests til verifikation af funktion, sikkerhed og ydelse.

For alle sikkerheds- og ydelsesparametre henvises i standarden til relevante teststandarder.

Standarden kan anvendes til certificering.

7.5.2 Brintgeneratorer baseret på brændselsomdannelses-teknologier (reformer mv.)

ISO 16110-1:2007

Hydrogen Generators using Fuel Processing Technologies – Part 1: Safety

En revisionsproces i 2010 resulterede i december 2010 i en bekræftelse af 2007 udgaven.

Denne standard omhandler sikkerhedsforhold og test heraf og dækker elektrolyseenheder med *en kapacitet på under 400 Nm³/h*, der konverterer et brændstof til en hydrogenrig blanding beregnet til fx brændselscellesystemer eller hydrogentankningsanlæg.

Følgende brændstoffer er omfattet

- Naturgas eller andre metanholdige gasser som fx biogas
- Olierivater som fx diesel, benzin, petroleum og LPG
- Alkoholer, estere, æter, aldehyder, ketoner, Fischer-Tropsch brændstoffer
- Andre gasformige brændsler med hydrogen som fx bygas og syntesegas

Standarden kan anvendes for udstyr til kommerciel, industriel eller privat brug, både inden – og udendørs

ISO 16110-2:2010

Hydrogen Generators using Fuel Processing Technologies – Part 2: Test Methods for the Performance (efficiency)

Standarden omfatter testprocedurer til verifikation af drifts- og miljømæssige forhold for de i Part 1 beskrevne anlæg, herunder virkningsgrader, driftsfleksibilitet, hydrogenkvalitet (også under transientdrift).

7.5.3 Standard for brinttankstationer for gasformig brint:

Tankningsanlæg for brintkøretøjer vil typisk bestå af

- Brintgenerator eller

- Flaskebatterier eller tubetrailer (ved ekstern produktion)
- Komprimeringsenhed
- Højtrykslager
- Tankningsenhed

For mindre anlæg men lav udnyttelsesgrad vil lokal brintgenerering ikke kunne svare sig. Brintforsyning vil i sådanne tilfælde med fordel kunne ske via forsyning fra flaskebatterier eller tubetrailers, der leveres med lastbil til slutlokaliteten. Brint leveres på gasform ved et tryk på 200-300 bar og skal herefter lokalt komprimeres til omkring 400 eller 800 bar for at kunne tanke brintbiler der som standard enten har et maksimalt tryk på 350 eller 700 bar. I udlandet ses ofte levering af brint på flydende form, der så lokalt genfor-gasses og komprimeres til nødvendigt tryk. Flydende brint vil ofte være en effektiv måde at kunne overholde de ret strenge krav til renhed iht. nedenstående standard ISO 14687-2.

Generelt gælder, at anlægget skal overholde myndighedskrav gældende for stationære brintanlæg, som anført i de øvrige kapitler. Der foreligger en række mere eller mindre færdige standarder inden for området.

I 2008 udkom denne tekniske specifikation (TS):

ISO TS 20100:2008

Gaseous Hydrogen Service Stations

Denne specifikation er basis for arbejdet med at udgivet en ny international standard. Status er, at den foreligger som DIS (draft international standard) udkast, og det er uvist, hvornår den udkommer.

Fokus er offentlige eller interne flåde tankstationer for ren hydrogen og ikke naturgas/hydrogenblandinger. Den vil bl.a. indeholde noget om

- Sikkerhedsafstande
- Zoneklassificering (Bemærk at Beredskabsstyrelsens vejledning under alle omstændigheder skal følges!)
- Påfyldningssystemer

7.5.4 Standarder for brintkvalitet

ISO 14687 oversigt

ISO 14687 omfatter pt. tre mere eller mindre færdige standarder

ISO 14687-1:1999: Dette er den oprindelige standard, der groft beskriver krav til brintkvaliteter til alle mulige anvendelser. I takt med at brændselscelleteknologien er blevet udviklet, har man erkendt behovet for mere detaljerede og specifikke standarder til forskellige anvendelsesformål for brændselscellestakke. Det har betydet, at man pt. arbejder på at udvikle

- ISO 14687-2 for brint til PEM fuel cells i køretøjer til off. vej
- ISO 14687-3 for brint til PEM fuel cells i stationære anlæg

Samtidig har man udgivet en korrektion til ISO 14687-1. Den hedder ISO 14687-1 Cor 2:2008 og heri er netop PEM brændselsceller fjernet fra gyldighedsområdet.

7.5.5 Brintkvalitet til køretøjer:

ISO TS 14687-2:2008

Hydrogen Fuel – Product Specification, Part 2: PEM fuel cell applications for road vehicles

I 2008 udkom den ovennævnte tekniske specifikation (TS) – Denne specifikation er basis for arbejdet med at udgivet en ny international standard. Status er, at den foreligger som et godkendt DIS (draft international standard) udkast og forventes indenfor et par år at udkomme som international standard.

I TS 14687-2 stilles en række strenge krav til renheden. Disse krav svarer stort set til, hvad der p.t. kræves af bilfabrikkerne ved drift af demoflåder af brændselscellekøretøjer.

I tabel 1 sammenlignes forskellige standarders krav med kommercielt tilgængelige kvaliteter fra Linde. Søjlen "Limits" angiver kravene i den amerikanske standard SAE J-2719. De anførte krav svarer omtrent til kravene i ISO TS 14687-2.

Constituent	Chemical Formula	Limits (ppm)	Linde-EU Grade 5.0*	CGA G-4.3 Grade 4.5
Total non hydrogen components	Grade 99.97	300	<50*	<50
Total non-hydrogen, non-helium	Grade 99.99	100	<10	<10
Water	H ₂ O	5	<5	<5
Total Hydrocarbons	CH ₄ , C _x H _y	2	<1	<1
Oxygen	O ₂	5	<2	<2
Helium (*not included in assay)	He	300	<50*	<50
Inerts (Nitrogen and Argon)	N ₂ + Ar	100	<10	<10
Carbon Dioxide	CO ₂	1	<1	<1
Carbon Monoxide	CO	0.1	ND/ <0.1	ND/ <0.1
Total Sulfur	Includes: H ₂ S, COS, CS ₂	0.001	ND / <0.001	ND / <0.001
Formic Acid	CHOOH	0.2	ND/ <0.1	ND/ <0.1
Ammonia	NH ₃	0.1	ND/ <0.1	ND/ <0.1

Note that this is a draft copy for comments and not for public release

Tabel 1: Sammenligning af brintspecifikationer i standarder og kommercielt tilgængelige kvaliteter. /2/

Disse krav, der er et resultat af de nuværende erfaringer med hensyn til hvad urenheder betyder for levetid af brændselscellestakke, forventes også at være gældende i væsentligt omfang i den kommende internationale standard. Det bør nævnes, at udstyr til gasanalyser for verifikation af disse krav er særdeles investeringstungt, og det vurderes at udstyret pt. ikke i fuldt omfang forefindes et samlet sted i DK.

7.5.6 Brintkvalitet til stationære PEM baserede brændselscelleanlæg

ISO/DIS 14687-3

Hydrogen fuel – Product specification – Part 3: Proton exchange membrane (PEM) fuel cell applications for stationary appliances.

Standarden foreligger som udkast og forventes at udkomme som standard i løbet af et par år.

Standarden beskriver 4 forskellige brintkvaliteter til stationære PEM baserede anlæg

- Type I Grade E "Reformate A" for anlæg med høj effektivitet og lav ydelse, der skal forsynes med reformat, hvor brintandelen på molba-

sis udgør 60-80 %. Kvalitetskravene er en del lavere end for brint til køretøjer.

- Type I grade E "Reformate B" for anlæg med høj ydelse, der skal forsynes med reformat, hvor brintandelen på molbasis udgør mindst 60 %. Kvalitetskravene er på niveau med kravene i 14687-2 for brint til køretøjer.
- Type I grade E "99 hydrogen" for anvendelser der behøver gasformig brint. Kvalitetskravene er på niveau med kravene i 14687-2 for brint til køretøjer.
- Type II Grade E "99 hydrogen" for anvendelser der behøver væskeformig brint. Kvalitetskravene er på niveau med kravene i 14687-2 for brint til køretøjer.

7.6 Standarder og vejledninger vedr. brintdistribution

- EIGA IGC Doc 121/04/E Hydrogen Transportation Pipelines. Globally harmonized document.
- ASME B31.12-2008 Hydrogen Piping and Pipelines

Begge standarder tager udgangspunkt i procesindustriens behov.

Det kan fx nævnes, at polymer ikke indgår som anbefalet rørmateriale. Endvidere er det normal praksis at brintrør ikke graves ned. Denne praksis letter overvågning af rørenes tilstand, men betyder samtidig at polymer fx af brandmæssige årsager ikke anbefales.

8 Gassikkerhedsforhold for brint i relation til andre gasser

I det følgende vil hovedsagelig de forhold, der har sikkerhedsmæssig betydning, blive beskrevet. Der vil blive sammenlignet med tilsvarende egenskaber for mere almindelige brændstoffer som benzin og naturgas.

Kort sagt:

- Brint er lettere end alle andre stoffer.
- Brint har ved rumtemperatur en meget lav densitet i forhold til luft og dermed stor opdrift.
- Brint diffunderer hurtigere gennem luft end andre gasformige brændsler.
- Brint er farveløs, lugtfri, smagsløs og umiddelbart ugiftig.
- Brints antændelsesområde dækker over meget store koncentrationsforskelle.
- Brintflammen er usynlig i dagslys.
- Brints tændenergi er ved visse koncentrationer meget lav. Ved en koncentration på 15-45 % ligger den på 10-20 % af benzins tændenergi.
- Brints flammehastighed er i visse koncentrationer højere end andre brændsler.
- Brints antændelsestemperatur er væsentlig højere end fx benzins.
- Brint er detonerbart over et stort koncentrationsområde, når det er inde lukket - men ellers er det svært.

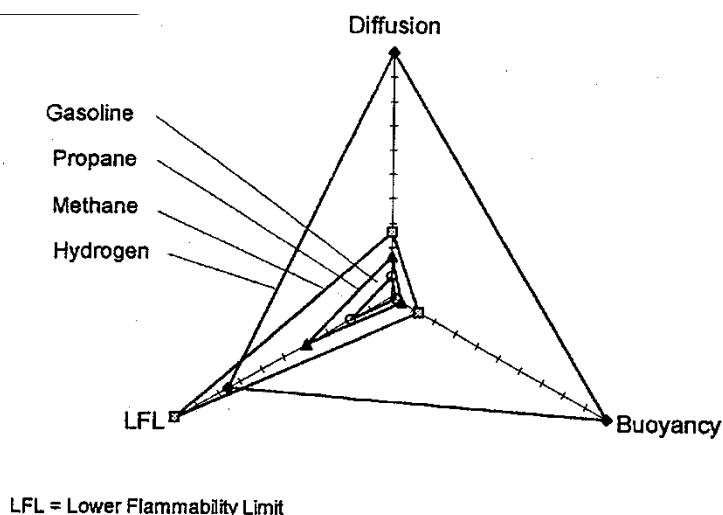
I oversigtsform

Tabel 2: *Sammenligning af sikkerhedskarakteristika for udvalgte brændsler*
/1/

	Brint	Naturgas	Propan	Benzin
Opdrift (rel. massefylde)	0,07	0,55	1,52	4
Diffusion (cm ² /s)	0,61	0,16	0,10	0,05
Nedre tændgrænse (% i luft)	4	4	2	1
Min. tændenergi (mJ)	0,02	0,29	0,3	0,24
Do. Ved nedre tændgrænse	0,3	0,3	0,3	0,3
Selvantændingstemperatur min. (°C)	520	630	450	230
Detonationsgrænse, nedre	13-18	6,3	3,1	1,1

(konc. % i luft)				
Flammehastighed (m/s)	2,7	0,37	0,47	0,3

Når man skal vurdere *risikoen for antændelse* ved lækager, er det først og fremmest *opdrift, diffusion, nedre tændgrænse samt tændenergi*, der betyder noget. For de tre førstnævnte parametres vedkommende kan dette illustreres således, se Figur 2

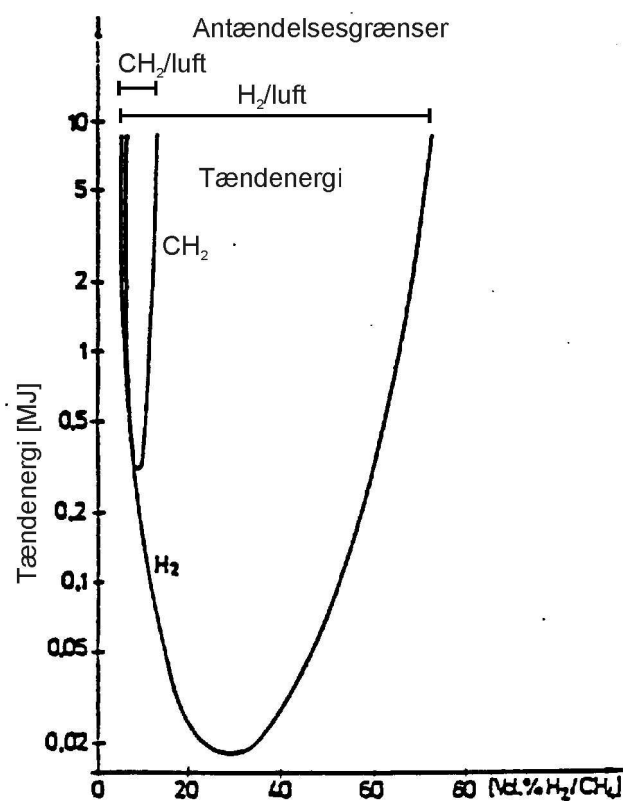


Figur 2: Illustration af antændelsesrisiko. Afbildning af opdrift, diffusion og nedre tændgrænse. De største værdier er mest sikre, dvs. mht. disse parametre er brint mest sikkert!! /1/

Brints tændenergi varierer usædvanlig meget som funktion af koncentrationen. Ved lave og høje koncentrationer er den på niveau med de øvrige brændsler til køretøjer såsom benzin og naturgas, men i det mellemliggende område falder tændenergien op til en faktor 100. Se Figur 3.

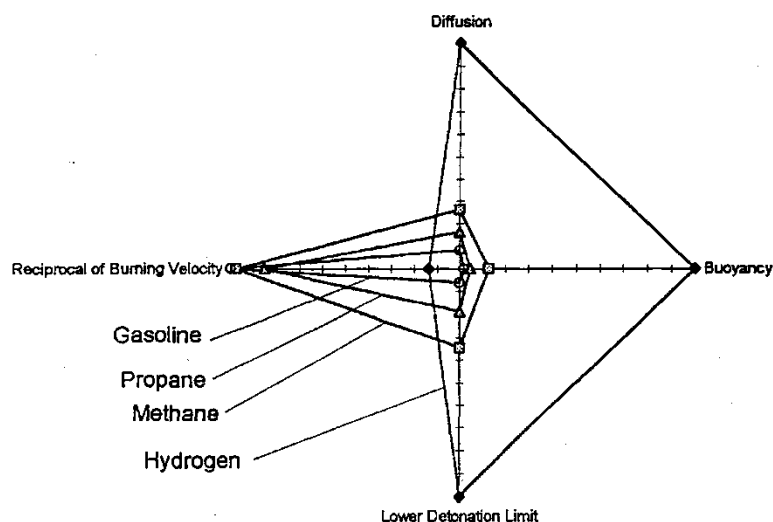
Som tidligere nævnt viser erfaringer, at der sker antændelse af brint i 80 % af de registrerede driftsuheld, og størstedelen medfører eksplosion, dvs. en deflagration eller en detonation*. Dette indikerer, at brints lave tændgrænse i et stort koncentrationsområde i praksis medfører en øget risiko for antændelse - til trods for at de øvrige betydende parametre indikerer det modsatte.

* Ved deflagration, der det mest almindelige, foregår flammeudbredelsen med under lydhastighed og maks. tryk er 8-9 bar. Ved detonation sker udbredelsen over lydhastighed og maks. tryk kan være op til cirka 20 bar. Væsentlig mere ødelæggende end deflagration.



Figur 3: Tændenergi som funktion af brint/metanandel i luft

Når man skal vurdere *risikoen for detonation*, er det først og fremmest nedre *detonationsgrænse*, *opdrift*, *diffusion* og *flamme­hastighed*, der betyder noget. Disse størrelser kan ligeledes illustreres med en polygon i et koordinat-system, hvor de sikreste værdier er de største. Derfor er der afbildet den inverse flammehastighed. Se Figur 4.



Figur 4 Illustration af detoneringsrisiko for forskellige brændsler. Det ses, at brint har mindst sandsynlighed for at nå en detonerbar gassky. Såfremt en eksplosion opstår, er der dog størst sandsynlighed for, at en brintsky overgår fra deflagration til detonation. /1/.

Konklusion: Ved en sammenligning af brændslerne naturgas, propan, brint og benzin i køretøjer når man overraskende frem til, at *brint mht. detonation er mere sikker* end benzin og propan og naturgas /4/. Omkring *risiko for antændelse af udslip vurderes brint samlet set at være mindre sikkert*, når der er tale om større udslip på grund af den lave tændenergi i et stort område. Når der er tale om små, langsomt sivende utætheder, vurderes brint at være mere sikkert end de øvrige brændsler på grund af brints opdrifts- og diffusionsegenskaber. *Forudsat at der altid er en passende ventilation!* Positive faktorer for sikkerheden under realistiske drifts- og uheldsforhold er brints stærke opdrifts- og spredningsegenskaber, relativt høje tændgrænse og detonationsgrænse. De negative faktorer for sikkerheden: lav tændenergi, stort antændelsesområde, høj flammehastighed og detonationsvillighed vurderes i gennemtænkte uheldsscenarier for mere eller mindre betydende.

9 Referancer

1. Sikkerhedsforhold og myndighedsgodkendelse ved brintanvendelse i køretøjer. Henrik Iskov. DGC. 2000.
2. Linde præsentation 2008. Bob Boyd.